What is an Industrial Designer?

An industrial designer is a creative professional who specializes in designing products, systems, and experiences that are both functional and aesthetically pleasing. They combine artistic skills with technical knowledge to develop innovative solutions that meet user needs, manufacturing requirements, and market demands. Industrial designers work across various industries, such as consumer electronics, furniture, automotive, and healthcare, collaborating with engineers, marketers, and manufacturers to bring their designs to life. Their expertise encompasses sketching, 3D modeling, prototyping, and user research, making them instrumental in the product development process from concept to production.

The Product Design Process Explained: The 2025 Guide

UPDATED ON DECEMBER 16, 2024

Great products fit seamlessly into our daily lives, but they don’t just happen by chance.

They’re the result of extensive research and problem-solving, creative ideation and innovation, and a ton of human empathy—otherwise known as the product design process.

Are you curious about how awesome products are designed and made? Want to know how product designers come up with their ideas and bring them to life?

Then, keep reading for a step-by-step breakdown of the product design process.

1. What is product design?

Product design is both a technical and creative discipline with one main goal: to conceive and create successful products.

In the context of product design, a successful product is one that fills a gap in the target market, helps to meet business objectives, and solves a specific problem for the people who will use it.

The product in question might be a physical product—like a selfie stick, a kettle, or an electric toothbrush—or a digital product, like a mobile app, an e-learning platform, or a video game. Product design encompasses anything, tangible or intangible, that can be used, experienced, or interacted with in some way.

Product design is steeped in research, strategy, and business. It considers the end users' needs and goals, as well as market trends and opportunities. It also factors in the big-picture vision for the business, considering how the product will help the company to drive revenue, attract new customers, and shape the brand identity.

And, most importantly, it covers the design of the product itself—focusing on the form, function, and appearance of the product—as well as the user experience (UX) it provides.

That’s product design in brief.

For a more in-depth definition, check out our beginner-friendly guide to product design—and explore how product design differs from UX design.

You can also see great product design in practice in our list of the **9 best examples of product design.**

2. What is the product design process?

The product design process is the general framework that product designers follow to create new products or improve existing ones.

The process is not set in stone. Every product designer has their own approach depending on both the product and the industry. You can imagine how the process of designing a vacuum cleaner might differ from the process of designing a mobile app, for example.

But, whatever the product, every product design process comprises thorough research, hands-on design, product testing, and continuous iteration. And most importantly, the product design process is always firmly rooted in design thinking.

What is design thinking, and what’s it got to do with the product design process?

Design thinking is a problem-solving framework that centers on the end user.

Despite the name, it’s not exclusively focused on design. Rather, it’s about coming up with solutions to real human problems. As such, design thinking can be applied in almost any context to address complex social issues, improve the human experience in educational or healthcare settings, devise business models and strategies, or resolve conflict and improve collaboration among teams.

The design thinking process focuses on cultivating empathy for the end user, defining a specific ‘human’ problem you’ll seek to solve, brainstorming potential solutions, and prototyping and testing those solutions.

The product design process closely mirrors this approach. It begins with extensive research to empathize with the target audience before moving on to ideation, design, and testing.

Ultimately, design thinking fosters an empathetic, user-first approach. By adopting a design thinking mindset, product designers can ensure that they’re prioritizing their target users. The better they understand their users’ needs, goals, and challenges, the more effectively they can design products that appeal to a specific audience.

In summary, design thinking and product design go firmly hand-in-hand! Now, let’s explore the product design process step by step.

3. The 5 steps in the product design process

The product design process can be broken down into five key steps:

- Research
- Ideation
- Design
- Testing and iteration
- Development and launch

Let’s zoom in to see what happens at each stage.

Step 1: Research

The first step in the product design process is research.

The research phase is critical for understanding the context around the product: the market it’s competing in, the users it will serve, and the business goals it should fulfill.

All of this context shapes the direction the product will take, ensuring that it’s something the target audience will actually want and need—and that it aligns with the business’s strategic objectives.

As part of product research, you might:

- Conduct user interviews, surveys, card sorting exercises, diary studies, and other forms of user research to get to know the target audience and empathize with their needs and pain-points.

- Create user personas (or user persona spectrums) to summarize and represent the different types of users and / or needs you want to design for.
- Define the end user problem your product should address.
- Conduct market research to uncover trends and opportunities.
- Research existing products in order to understand the competitive landscape and identify opportunities for differentiation.
- Conduct stakeholder interviews to understand the business goals the product should help to fulfill, as well as the long-term product vision.
- Collaborate with internal stakeholders to determine what resources are available, both technological and financial, for creating (or improving) the product.

The research phase is all about exploration, discovery, and understanding. Once you fully understand your target audience, your target market, and the business goals, you’re well-positioned to come up with a great product.

Step 2: Ideation

Next up in the product design process: ideation.

During the research phase, you defined the user problem you want to solve. Now the goal is to come up with potential solutions to that problem.

This step is closely modeled on design thinking, which views ideation as a strictly judgment-free zone. Designers are encouraged to ideate collaboratively, to think outside the box, and to focus on quantity over quality. Who knows what awesome ideas you'll come up with when you're given full creative freedom?!

Some popular ideation techniques used by product designers include:

- Group brainstorming sessions involving key stakeholders and fellow designers.

- Crazy 8s—a Design Sprint technique that involves sketching eight unique ideas in eight minutes, with the goal of rapid and diverse ideation.

- Mindmapping, a visual ideation technique that builds a map of interconnected ideas branching off from a central theme or concept.
- Reverse thinking—a lateral thinking technique that focuses on the exact opposite of what you want to achieve. For example, if your goal is to design a product or feature that improves the online dating experience for millennials, a reverse thinking approach would be to consider: How can we ensure a terrible online dating experience for millennials? The ideas you come up with for the opposite challenge may bring you closer to what your users actually need.

- Concept sketching and storyboarding to visually capture how different solutions might look and function. This helps to identify potential flaws and validate or disqualify ideas early on.

The ideation stage isn't about coming up with a fully-fledged, entirely feasible concept—at least not to begin with. But, as you work through different ideas, you'll naturally start narrowing it down to a handful of promising avenues that are worth exploring further.

What is an Industrial Designer?

When you combine creative design with manufactured items, you get an industrial designer—a creative professional with a unique skill set in "form and function."

Industrial design (ID) is the professional practice of designing the objects, devices, and products used by millions of people globally.

Industrial designers focus on a product's manufacturability, functionality, sustainability and physical appearance - ultimately contributing to the lasting value and experience a service or product provides for end users.

Employment Opportunities in Industrial Design

Industrial designers combine business, art, and engineering to develop concepts for manufactured products. The top jobs in this field are industrial designers, product designers, project managers, and design engineers.

These professionals develop concepts for manufactured products including electronic devices, home appliances, furniture, cars, toys, medical devices - really anything you see in the built environment. They create products people use every day.

Employers may post jobs with industrial design skills under different titles. Common alternative job titles include:

- Product Designer
- Industrial Designer
- Senior Industrial Designer
- Design Researcher
- Design Strategist
- Product Manager

Some examples of Industrial Design

Job Duties of an Industrial Designer

An industrial designer performs tasks such as:

- Meeting with clients to determine design requirements and creating physical design prototypes
- Conducting user research and market analysis
- Creating physical and digital prototypes
- Creating renderings or images on a computer or on paper that provide a visual of design concepts
- Using computer software to develop virtual models of designs
- Researching who will use a particular product, and the various ways it might be used
- Presenting designs to clients for feedback and approval
- Evaluating product function, appearance, and safety
- Determining feasibility, viability, and desirability
- Calculating production costs by examining manufacturing requirements, materials, and other supply chain considerations
- Working with other specialists, such as manufacturers and mechanical engineers, to evaluate whether their design concepts will meet consumer needs

What Does an Industrial Designer Do?

Industrial designers work closely with consumers to determine what types of designsperform best and capture target audiences. They also present, test, and develop new ideas for the manufacturing of everyday products.

Useful Skills for Industrial Designers

Industrial designers exhibit skills such as:

- Imagination and originality
- Research and collaboration
- The ability to articulate concepts concisely
- Meticulous attention to detail
- Drawing, mechanical drafting, and computer sketching
- Prototyping
- Product development
- Market savviness
- Logic and persuasiveness
- Great interpersonal skills
- Knowledge of computer software
- Comfortability in a manufacturing environment
- Adeptness at translating ideas into designs
- Information technology (IT) skills
- Industrial engineering industry expertise
- Balancing creativity with practicality
- Comfortability with machines, tools, and hardware

Software Proficiencies for Industrial Designers

An industrial designer's main skill set revolves around sketching out ideas and schematics for how specific products should look. These sketches are often rendered in 3D software that takes a product and brings it into form.

Industrial designers have computer-aided design (CAD) software skills for computer-aided industrial design (CAID) or 3D design software.

These professionals are also skilled at using other types of software, such as:

- Industry-specific modeling software such as Rhino, Keyshot, Siemens NX, Autodesk Alias, and Autodesk Inventor
- AutoCAD, TinkerCAD
- Adobe Creative Suite
- SolidWorks for mechanical design
- Open-source programs such as FreeCAD and blender

INDUSTRIAL DESIGN DEFINITION HISTORY

In September of 1959 the first Icsid* Congress and General Assembly were held in Stockholm Sweden. The Congress was the first of what would become the largest world event in Icsid's calendar – one that still continues to this day. The Congress and GA were restricted solely to Icsid members, which had already grown to 23 societies from 17 countries. It was on this occasion that the Icsid Constitution was officially adopted, along with the first definition of industrial design, which read as follows:

An industrial designer is one who is qualified by training, technical knowledge, experience and visual sensibility to determine the materials, mechanisms, shape, colour, surface finishes and decoration of objects which are reproduced in quantity by industrial processes. The industrial designer may, at different times, be concerned with all or only some of these aspects of an industrially produced object.

The industrial designer may also be concerned with the problems of packaging, advertising, exhibiting and marketing when the resolution of such problems requires visual appreciation in addition to technical knowledge and experience.

The designer for craft based industries or trades, where hand processes are used for production, is deemed to be an industrial designer when the works which are produced to his drawings or models are of a commercial nature, are made in batches or otherwise in quantity, and are not personal works of the artist craftsman.

The 1960s also witnessed a growth within Icsid's membership to include a number of non-capitalist countries of the time. This changed Icsid's outlook from being somewhat insular to being an inclusive and truly outward-looking organization that transcended political boundaries. In this sense, Icsid became a bridge between two worlds, where industrial designers from all backgrounds could meet, exchange and learn from one another. Icsid members relished in the spirit of collaboration that was inspired by the inclusive nature of Icsid's work.

Icsid also continued to work on matters of professional practice during this time, adopting and revising the definition of industrial design, which read as follows:

The function of an industrial designer is to give such form to objects and services that they render the conduct of human life efficient and satisfying. The sphere of activity of an industrial designer at the present embraces practically every type of human artefact, especially those that are mass produced and mechanically actuated.

The structure and focus of Icsid was becoming much more diverse. Commencing in 1963, Icsid was granted special consultative status with UNESCO, with whom Icsid would subsequently work on many developmental projects, using design for the betterment of the human condition. In 1969, a third definition of industrial design was proposed by Tomas Maldonado, it read as follows:

Industrial design is a creative activity whose aims is to determine the formal qualities of objects produced by industry. These formal qualities are not only the external features but are principally those structural and functional relationships which convert a system to a coherent unity both from the point of view of the producer and the user. Industrial design extends to embrace all the aspects of human environment, which are conditioned by industrial production.

By 1971, however, Icsid had removed any definition from the constitution in a motion passed at the Ibiza General Assembly. The motion symbolised a fundamental shift in the outlook of the organization.

*The World Design Organization was formerly known as International Council of Societies of Industrial Design

An industrial designer is a creative professional specializing in the conceptualization and development of products that marry functionality with aesthetic appeal. These professionals operate at the intersection of art, business, and engineering, tasked with envisioning and crafting objects that enhance usability and consumer experience. Their scope of work stretches across various industries, from automotive and furniture design to consumer electronics and household goods. Drawing from a deep well of knowledge in materials, manufacturing processes, and human-centered design principles, industrial designers play a critical role in shaping the tangible products that populate our daily lives.

Beyond mere visual appearances, industrial designers consider a multitude of factors such as ergonomics, sustainability, and market trends to create products that are not only attractive but also practical and responsible. They engage in extensive research and iterative prototyping, collaborating closely with engineers, manufacturers, and marketing teams to ensure that the final product can be produced feasibly and align with both consumer needs and strategic business goals. By effectively balancing innovative design with user-centric functionality, industrial designers help companies establish strong brand identities and secure competitive advantages in their respective markets.

What Does An Industrial Designer Do?

An industrial designer plays a critical role in shaping the products we use every day by blending creativity, technical knowledge, and user-centered principles to create functional, aesthetically pleasing, and innovative designs. At the heart of their work is the intricate task of envisioning and developing new products or improving existing ones, spanning a vast array of industries from electronics and furniture to automobiles and medical devices. Industrial designers begin by understanding the needs and desires of consumers, often conducting research, interviews, and user-testing to inform their design process. They collaborate closely with engineers, marketers, and manufacturers to ensure that their concepts are not only visually compelling but also feasible and cost-effective to produce. Balancing form and function, these designers meticulously draft and refine sketches, create 3D models, and develop prototypes, all while considering materials, ergonomics, and sustainability. Their ultimate goal is to enhance the user experience and solve real-world problems through innovative design solutions, making everyday products more useful, efficient, and enjoyable. By fusing artistic sensibilities with pragmatic considerations, industrial designers help turn imaginative ideas into tangible, impactful realities that resonate with consumers and meet the demands of modern living.

How To Become An Industrial Designer?

Becoming an industrial designer involves cultivating a blend of creativity, technical skills, and an understanding of user needs. Start by earning a bachelor's degree in industrial design or a related field to build a strong foundation in design principles, materials, and engineering. Develop a compelling portfolio that showcases your innovative ideas and practical solutions. Gain hands-on experience through internships and professional projects to refine your skills and network within the industry. Staying current with technological advancements and design trends will help you evolve as a proficient industrial designer.

Education
Bachelor's degree Avg. Experience 0-1 years

Industrial Designer Career Paths

A career path in Industrial Design typically begins with an educational foundation in design principles, often obtained through a bachelor's degree in Industrial Design or a related field such as product design or engineering. Aspiring industrial designers learn essential skills in sketching, 3D modeling, materials science, and manufacturing processes. Upon graduation, entry-level positions such as junior designer or design assistant offer opportunities to gain hands-on experience and develop a professional portfolio. As industrial designers progress, they often collaborate with engineers, marketers, and manufacturers to create functional and aesthetically pleasing products.

With experience, industrial designers can advance to senior roles or specialize in areas like user experience (UX) design, sustainable design, or digital product design. Many designers also opt to further their education with advanced degrees or certifications, enhancing their expertise and marketability. Leadership positions such as design manager or creative director become accessible after establishing a robust portfolio and demonstrating an ability to lead projects and teams. Some industrial designers choose entrepreneurial paths, starting their own design consultancies or launching innovative products. Regardless of the route taken, continuous learning and adaptation to new technologies and trends are crucial for career growth in this dynamic field.

Industrial Designer Education

The most common degrees for an Industrial Designer are Bachelor's degree (78.27% of jobs require this), Master's degree (17.39%), Associate's degree (4.35%).

Industrial Designer Degrees

Bachelor's degree78.27%
Master's degree17.39%
Associate's degree4.35%

Top Skills For An Industrial Designer

We tracked the skill requirements from thousands of job postings for an Industrial Designer. Consider highlighting these skills in your resume to stand out from other candidates. We found 2% of Industrial Designer jobs listed Research in their requirements, 2% listed Innovation, and 2% listed Product Design.

Research2%
Innovation2%
Product Design2%
Creativity2%
Rendering2%
Ergonomics2%

User Brain: Harnessing Cognitive Science for Intuitive Design

Neuromarketing

September 30, 2024

The key to designing intuitive digital experiences lies in understanding the user's brain—a complex, cognitive puzzle that UX designers must solve to create interfaces that feel effortless and engaging. This concept, often referred to as the "user brain," has become increasingly crucial in the realm of modern digital experiences. As we navigate an ever-expanding digital landscape, the ability to craft interfaces that resonate with our cognitive processes has never been more important.

But what exactly is the user brain? It's not just a catchy phrase; it's a fundamental approach to design that draws upon the principles of cognitive science to create user experiences that feel natural and intuitive. By understanding how our brains process information, make decisions, and form memories, designers can craft digital environments that work in harmony with our mental processes rather than against them.

The importance of this approach cannot be overstated. In a world where attention is a precious commodity, and users have countless options at their fingertips, designing for the user brain can mean the difference between an app that becomes a daily habit and one that's quickly forgotten. It's about more than just making things look pretty; it's about creating experiences that feel like second nature.

To truly grasp the concept of user brain, we need to take a quick dive into the world of cognitive science. This interdisciplinary field combines insights from psychology, neuroscience, and computer science to understand how the mind works. For UX designers, it's a goldmine of knowledge that can inform every aspect of the design process.

Understanding the User's Mental Model

At the heart of designing for the user brain is the concept of cognitive load theory. This theory suggests that our working memory has a limited capacity, and when we overwhelm it with too much information or complexity, our ability to process and retain information suffers. It's like trying to juggle too many balls at once – eventually, something's got to give.

This is where the idea of schema comes into play. Our brains are constantly trying to make sense of the world around us by organizing information into mental frameworks or schemas. When we encounter a new interface, we automatically try to fit it into our existing schemas. If it aligns well, we find it intuitive. If it doesn't, we struggle.

Think about the first time you encountered a smartphone interface. It probably felt a bit overwhelming at first. But as you used it more, your brain created new schemas to understand and navigate this digital environment. Now, you probably don't even think about how to use your phone – it just feels natural.

Perception and attention play crucial roles in how we interact with digital interfaces. Our brains are constantly filtering the massive amount of sensory information we receive, focusing on what's deemed important and ignoring the rest. This is why Brain Hook: The Psychological Technique That Captures Attention is so crucial in design. By understanding how to capture and direct user attention, designers can create more engaging and effective interfaces.

Memory and recall are also key considerations. How easily can users remember where to find certain features? How intuitive is the navigation? These questions tap into our understanding of how the brain forms and retrieves memories. By aligning interface design with these cognitive processes, we can create experiences that feel more natural and require less mental effort to use.

Applying User Brain Principles in Design

Now that we’ve laid the groundwork, let’s explore how these principles translate into practical design strategies. One of the most fundamental aspects is visual hierarchy and information architecture. Just as our brains organize information into schemas, good design organizes visual elements in a way that guides the user’s attention and helps them make sense of the interface.

This is where Gestalt principles come into play. These principles, derived from psychology, describe how our brains tend to group and organize visual elements. For example, the principle of proximity states that we perceive elements that are close together as being related. By leveraging these principles, designers can create interfaces that feel intuitive and easy to navigate.

Color psychology is another powerful tool in the designer’s arsenal. Colors can evoke emotions, guide attention, and even influence decision-making. By understanding the psychological impact of different colors, designers can create interfaces that not only look good but also feel good to use.

Microinteractions and feedback loops are the unsung heroes of user experience. These small, often overlooked details can make a huge difference in how intuitive an interface feels. A subtle animation when you like a post, the satisfying “whoosh” sound when you send an email – these microinteractions provide immediate feedback that aligns with our brain’s expectation of cause and effect.

User Brain and Decision-Making

Understanding how users make decisions is crucial for creating interfaces that feel natural and effortless. This is where choice architecture comes into play. By carefully structuring the options presented to users, designers can guide decision-making without overwhelming the user’s cognitive resources.

However, it’s important to be aware of decision fatigue. Our brains have a limited capacity for making decisions, and each choice we make depletes this resource. This is why many successful apps and websites aim to reduce the number of decisions a user needs to make, especially for routine tasks.

Heuristics and cognitive biases also play a significant role in user behavior. These mental shortcuts help us make quick decisions, but they can also lead us astray. By understanding these biases, designers can create interfaces that work with our natural thought processes rather than against them.

This brings us to the topic of persuasive design techniques. While these can be powerful tools for guiding user behavior, they also raise important ethical considerations. As designers, we have a responsibility to use these techniques in ways that benefit the user, not just the business. It’s a delicate balance that requires constant reflection and adjustment.

Measuring and Optimizing for User Brain

So how do we know if our designs are truly aligning with the user's cognitive processes? This is where measurement and optimization come in. Eye-tracking studies and attention heat maps can provide valuable insights into how users visually process an interface. These tools allow designers to see exactly where users are looking and for how long, helping to identify areas of confusion or interest.

A/B testing is another powerful tool for cognitive optimization. By comparing different versions of an interface, designers can see which one performs better in terms of user engagement and task completion. This data-driven approach allows for continuous improvement based on real user behavior.

User feedback and qualitative research methods are equally important. While quantitative data can tell us what users are doing, qualitative research helps us understand why they're doing it. This deeper understanding of user motivations and thought processes is crucial for designing truly intuitive interfaces.

In recent years, neuromarketing techniques have also made their way into UX research. These methods use neuroscience tools to measure brain activity and physiological responses as users interact with digital interfaces. While still a developing field, it offers exciting possibilities for gaining deeper insights into the user brain. As explored in Brain Sells: Unlocking the Power of Neuromarketing in Modern Advertising, these techniques are already revolutionizing how we approach user experience design.

Future Trends in User Brain Research

As technology continues to evolve, so too does our understanding of the user brain. Artificial intelligence and machine learning are opening up new possibilities for predicting user behavior and creating more personalized experiences. Imagine an interface that adapts in real-time to your cognitive state, presenting information in the most optimal way for your current mental capacity.

Virtual and augmented reality interfaces present exciting new challenges and opportunities for user brain design. These immersive technologies have the potential to create experiences that feel more natural and intuitive than ever before, but they also require a deep understanding of how our brains process three-dimensional space and movement.

Personalization and adaptive user experiences are likely to become increasingly sophisticated. As we gather more data about individual users' cognitive preferences and behaviors, we can create interfaces that feel tailor-made for each person. This level of personalization could dramatically reduce cognitive load and make digital experiences feel more effortless than ever.

Accessibility and inclusive design for diverse cognitive abilities is another crucial area of development. As our understanding of neurodiversity grows, so too does our ability to create interfaces that work well for people with different cognitive strengths and challenges. This isn't just about accommodating disabilities; it's about recognizing and designing for the full spectrum of human cognitive diversity.

The concept of Grug Brain: Exploring the Concept and Its Impact on Modern Thinking offers an interesting perspective on how our primitive brain functions still influence our interactions with modern technology. Understanding these primal instincts can help designers create interfaces that feel more natural and satisfying to use.

As we look to the future, it's clear that the field of user brain research is only going to become more important. The Brain Boost Search Engine: Enhancing Cognitive Performance with Digital Tools is just one example of how our growing understanding of cognitive science is being applied to create more effective digital tools.

In conclusion, designing for the user brain is not just a trend; it's a fundamental shift in how we approach user experience design. By understanding and applying cognitive science principles, we can create digital experiences that feel intuitive, engaging, and even delightful to use.

The relationship between cognitive science and UX design is evolving rapidly, with new insights and technologies constantly emerging. As designers, it's our responsibility to stay informed about these developments and to continually refine our approach to creating user-centered experiences.

So, what's the call to action for designers? It's simple: prioritize user brain considerations in every aspect of your design process. From the initial concept to the final polish, always ask yourself: "How does this align with the user's cognitive processes?" By doing so, you'll not only create more effective and engaging interfaces but also contribute to a digital world that works in harmony with our minds rather than against them.

Remember, great design isn't just about making things look good – it's about making them feel right. And that feeling comes from a deep understanding of the most complex and fascinating interface of all: the human brain.

References

1. Kahneman, D. (2011). Thinking, Fast and Slow. Farrar, Straus and Giroux.

2. Norman, D. (2013). The Design of Everyday Things: Revised and Expanded Edition. Basic Books.

3. Weinschenk, S. (2011). 100 Things Every Designer Needs to Know About People. New Riders.

4. Krug, S. (2014). Don’t Make Me Think, Revisited: A Common Sense Approach to Web Usability. New Riders.

5. Eyal, N. (2014). Hooked: How to Build Habit-Forming Products. Portfolio.

6. Johnson, J. (2014). Designing with the Mind in Mind: Simple Guide to Understanding User Interface Design Guidelines. Morgan Kaufmann.

7. Ariely, D. (2008). Predictably Irrational: The Hidden Forces That Shape Our Decisions. HarperCollins.

8. Spool, J. M. (2018). The UX Tipping Point. UIE. https://articles.uie.com/the-ux-tipping-point/

9. Nielsen, J. (2000). Designing Web Usability: The Practice of Simplicity. New Riders Publishing.

10. Thaler, R. H., & Sunstein, C. R. (2008). Nudge: Improving Decisions About Health, Wealth, and Happiness. Yale University Press.

Step 3: Design

After ideation comes design—the part of the product design process where ideas are brought to life!

During the design phase, product ideas are developed into more refined concepts. The focus turns to how the product might look and function, as well as the materials and / or technologies that will be used to build the product.

This step in the process varies considerably depending on the product in question. For digital products such as apps and websites, the design stage might include:

- Defining the product's information architecture.
- Creating low-fidelity sketches and wireframes to map out the initial structure of the product.
- Applying UX design principles to ensure that the product is usable, user-friendly, and accessible.
- User interface (UI) design; creating all the visual and interactive elements that determine how the product looks and functions. This includes things like icons, colors, typography, buttons, animations, and images.
- Working with a UX writer to craft the messaging and microcopy that will feature throughout the product.
- Creating interactive, high-fidelity prototypes that replicate how the product will look and function once it's developed.

For physical products, the design phase might include:

- Sketching and rendering—using computer software to create 2D or 3D digital mock-ups of the product's form and features.

- CAD modeling—using CAD software to develop more detailed 3D product models.

- Determining which materials will be used to build the product and the various product components or features.

- Creating physical prototypes to replicate how the product will look and function in real life.

No matter what type of product you're designing, the design phase focuses on the product's form and function, as well as the overall user experience it provides. The end goal, of course, is to design a product that's easy and enjoyable to use—and that effectively solves a specific user problem.

The design phase doesn't result in a market-ready product, though. Far from it! Usually, you'll end up with an MVP—a minimum viable product—that you can take forward for product testing.

Human Factors in Product Design: Meaning, Principles and Examples

Christian Bourgeois . December 20, 2024

Have you ever tried to open a package and found it extremely difficult, requiring you to reach for a tool? Have you ever tried to pull on a door handle only to find out it’s a push door? If so, it’s easy to think it’s your fault, but in reality, poor human factors design is likely at play.

When designing a product, it’s crucial to keep the end user top of mind. In this post, we’ll show you the importance of human factors in product design, teach you valuable principles, and show you examples of products we designed at StudioRed with human factors in mind.

What Are Human Factors in Design?

Human factors design is about designing products with particular attention to human capabilities and limitations to improve usability. It also considers other systems and the environment in which the product will exist. The end goal is to create products and systems that are efficient, effective, safe, and simple to use.

Researching your target audience is also crucial in this process. It helps narrow your focus on specific design aspects to create an optimal user experience for the product's users.

The Importance of Considering Human Factors in Product Design

While it's important to put energy and thought into a product's features, users should be able to seamlessly use those features. Considering users' physical and cognitive capabilities and limitations allows designers to create functional products that are intuitive and enjoyable to use.

When human factors design is part of your process, products become more accessible to a wide range of users, including those with disabilities. By creating a product that suits a diverse group of people, you will have much more success meeting users' needs.

Additionally, well-designed products can reduce user error, increase productivity, and enhance overall user satisfaction. Making human factors design a priority allows your products to meet and exceed user expectations.

Human Factors vs. Ergonomics vs. UX

You may sometimes see human factors, user experience (UX), and ergonomics used interchangeably, but each has a distinct yet complementary role in creating user-friendly products. Here are the differences between the terms:

- **Human factors:** This broad discipline considers human capabilities, limitations, and behavior when interacting with products and systems. It looks at cognitive abilities, environmental factors, and physical characteristics.
- **Ergonomics:** A subset of human factors, ergonomics is the study of the physical interaction between humans and products. Ergonomics looks at factors like posture, reach, and physical exertion to create a comfortable and efficient design. Think of an ergonomic chair that supports your back or a keyboard that minimizes wrist strain.
- **UX:** UX design principles encompass the entire user journey when interacting with a product. It involves understanding user needs, emotions, and perceptions to create a positive and enjoyable experience throughout the product's use. For example,

a TV remote with good UX has an intuitive layout and may have extra features like backlit buttons and voice control.

Human factors and ergonomics lay the groundwork for creating usable and efficient products, whereas UX adds a layer of emotional appeal and user satisfaction to the experience. By combining these disciplines, designers can create products that enhance users' lives.

Human Factors Design Principles

You can overcome product design challenges by turning to the five principles of human factors design. These principles should guide your design team to look at your product from different angles and decrease the likelihood of missing something crucial for usability.

We also provide some examples of products we designed at StudioRed using these principles to help you when working on your next project.

1. Ergonomics: The principle of ergonomics is about keeping people of all shapes and sizes in mind. Ergonomics includes a person's posture, reach, and force when using a product. This can also include accessibility features. Implementing ergonomics involves focusing on the extremes of human variability to ensure the design accommodates the broadest range of users and scenarios, inherently addressing the most typical use cases.

The image below is from a study for a biotech instrument focusing on comfort based on a user's height. By focusing on the extreme use case scenarios of 95th-percentile men and 5th-percentile women, the study aims to gauge how the product will feel with the lowest lab bench height. The primary consideration was the reach and clearance needs of the tallest user.

2. Cognitive load: This human factors principle involves minimizing mental effort by creating intuitive and easy-to-use products. Providing clear instructions or using familiar symbols and patterns minimizes cognitive load.

3. Consistency: Consistency in your product's look and function allows for a lighter cognitive load due to predictability. For example, levers may be placed at a consistent height from the floor to accommodate both seated and standing users.

4. Efficiency: This principle aims for users to complete a task in the shortest time possible. An example would be using an ergonomic study to consider already established user behavior, aiming to design products or systems that align with the user's already existing habits, patterns, and expectations. This approach leverages familiar behaviors to minimize the learning curve and the cognitive and physical effort.

In the following image, you can see our team working on a self-checkout system for retail stores. We analyzed the existing workflow from both the clerk's and customer's perspectives to ensure efficiency for anyone using the product. The top row shows the process of the clerk reaching for a product from behind, while the bottom row shows how a customer would interact with the front of the device.

5. Familiarity: Products should have some familiarity to reduce the chance of confusion and additional cognitive load when used for the first time. Products with similar features to others in an ecosystem or comparable products enhance predictability and reduce cognitive effort.

Human Factors Considerations When Designing a Product

As you set out to create a plan for human factors in product design, it’s helpful to consider the following:

- **Simplify onboarding:** Bringing users in for testing should be seamless, and it starts with breaking down tasks into smaller, manageable steps while providing the user with clear guidance at each stage. Avoid overwhelming the user with information when providing instructions by prioritizing the most critical features and functionality.
- **Give users a sense of control:** Empowering users with a sense of control is paramount. Clear feedback, intuitive controls, and the ability to customize settings can help you foster a positive user experience.
- **Provide error handling:** Consider who will use the product and what challenges they may encounter when interacting with it. Adjust the design and provide audible cues or visual alerts if something is wrong to minimize the impact of potential user errors.

When we designed the warehouse scanner in the image below, we acknowledged that many warehouse workers wear gloves. This makes *it difficult to press the buttons effectively, so we evaluated the button placement, size, spacing, and force requirements to accommodate gloved hands.*

- **Implement clear feedback mechanisms:** Similar to error handling, you can include physical, auditory, and visual feedback mechanisms. For example, a button or switch might click into place when turning a machine on, letting the user know it worked.
- **Test for real-world usability:** When testing the product, ensure it's tested in scenarios the user is likely to encounter. A product for outside use will be designed differently than one used in an office.

Approaches To Identify Human Factors in Design

Designers use various techniques to identify opportunities for human factors in design. We've listed them below, along with some examples:

- **User testing:** During the testing phase, have a diverse group of people test multiple designs. This allows you to see how they interact with a product and get a variety of perspectives.

When redesigning the steering controls for a skid steer, we did a study on both the handles and the physical controls to make sure the user felt safe and stable when steering while also feeling comfortable.

- **Surveys:** Conducting surveys is a great way to gather insights and feedback. They can help you identify user needs and expectations, potential user limitations, and what features to prioritize. Surveys after testing allow you to gauge user satisfaction and the pain points they experienced.
- **Observation:** Gathering quantitative data, like completion times and error rates, can help you focus on specific aspects of the product when you make revisions.
- **Prototyping:** Prototypes take your vision of human factors and bring them to life in a test version. You can create inexpensive mockups of products to test your theories about ergonomics, efficiency, cognitive load, and other factors. Something as simple as a paper mockup can go a long way.

The following prototypes are for a warehouse scanner we designed. We wanted to evaluate the ergonomic tilt of the device — we were able to test for different hand sizes by using iterative foam mockups and 3D-printed prototypes.

Create User-Centric Designs

Human factors are critical if you hope to create a user-friendly product. Prioritizing usability leads to increased adoption, improved productivity, a positive brand image, and more. Here at StudioRed, we have an experienced team that applies the principles of human factors design to every product we create.

Our team has expertise in industrial design, engineering, and UX and UI. We help bring your product to life, from conception and prototyping to the final product. We work closely with each client to ensure their vision becomes reality while also satisfying users.

Get in touch today so we can work together to elevate your product design.

Your Ultimate Guide to Design for Manufacturing (DFM)

Christian Bourgeois . October 1, 2024

Design for Manufacturing (DFM) is the process of designing products with the manufacturing process in mind, optimizing for cost, efficiency, and quality.

The product development journey is rewarding, but it's not without its challenges. One of the most critical aspects of this journey, and one that can make or break your product's success, is Design for Manufacturing. As seasoned industrial designers, we've seen firsthand how DFM optimizes production, cuts costs, and boosts product quality.

In this guide, we'll share our expertise on DFM best practices, common pitfalls to avoid, and how to leverage DFM principles to create better products more efficiently.

What Is Design for Manufacturing?

Design for Manufacturing, or DFM, is the process of examining how to make a product easier, faster, and more cost-effective to produce without compromising on quality or functionality. This process involves considering various factors such as materials, manufacturing methods, assembly techniques, and the capabilities of the production facility.

"A famous designer told me, 'if you learn how things are made, you will be a better designer.'"

– Philip Bourgeois, Founder of StudioRed

DFM is critical for creating products that can be produced at scale efficiently and profitably. Without DFM, you risk ending up with a design that looks great on paper but is a nightmare to actually manufacture, leading to production delays, quality issues, and skyrocketing costs.

At StudioRed, we often start DFM conversations before a project officially kicks off. By considering manufacturing constraints and opportunities early, we can save significant time and money down the road.

DFM isn't just a one-time activity — it's a proactive, iterative process that spans the entire product development lifecycle. It starts with the initial concept and continues through design, engineering, prototyping, and production. At each stage, DFM considerations play a crucial role in shaping the product's design and ensuring its successful transition from concept to reality.

It's important to note that DFM is not a standalone concept. It's closely related to other design methodologies, such as Design for Assembly (DFA). While DFM focuses on optimizing individual parts for manufacturing, DFA concentrates on making the overall assembly process more efficient. Together, these concepts form what we call **Design for Manufacturing and Assembly (DFMA)**, a holistic approach to product design that considers both manufacturing and assembly aspects.

DFM Benefits

Implementing DFM principles can have a massive impact on the success of a product. Here are some of the key benefits we've experienced firsthand:

- **Lower production costs:** Optimizing designs for manufacturing can reduce material usage, minimize waste, and streamline production processes. This can lead to significant cost savings, especially at higher volumes.
- **Reduced risk:** DFM helps catch and correct potential manufacturing issues early before they turn into expensive production problems.
- **Faster time to market:** Considering manufacturing early on helps avoid major redesigns later in development. This can shave weeks or months off product launch timelines.
- **Improved product quality:** DFM helps eliminate design features that are prone to defects or variability in

manufacturing. The result is more consistent, higher-quality products.

- **Enhanced reliability and maintainability:** DFM principles often lead to simpler designs with fewer parts. This typically results in reliable products that are easier to maintain, service, and repair over their lifetime.
- **Increased production flexibility:** A DFM-optimized design can be more easily adapted to different manufacturing processes and scaled up or down as needed.
- **Improved communication and collaboration:** DFM fosters better communication and teamwork between design, engineering, and manufacturing teams.
- **Increased innovation:** DFM encourages creative problem-solving to optimize designs, often leading to innovative solutions.
- **Improved sustainability:** Optimizing material usage and manufacturing processes can reduce waste and energy consumption.
- **Greater customer satisfaction:** By offering higher-quality products delivered faster and at lower costs, you can exceed your customers' expectations and boost loyalty.

Design for Manufacturing Principles

By understanding and applying DFM's core principles, you can create designs optimized for efficient, high-quality production. These principles form the foundation of our approach to DFM at StudioRed and have proven invaluable in countless projects.

1. Minimize Part Count

Think of product development as a puzzle — the fewer pieces there are, the easier it is to put together. The same concept applies to manufacturing. Each part of your product represents a potential point of complexity, cost, and failure. Minimizing part count means:

- Decreased material costs
- Fewer components to source and inventory
- Reduced quality control steps
- Minimal assembly times
- Less opportunity for defects or errors

At StudioRed, we always challenge ourselves to look for opportunities to combine multiple functions into single parts or eliminate unnecessary components. For example, instead of using separate fasteners, can we design snap fits or living hinges that are integrated into the parts themselves?

Of course, there's a balance to strike. Overly complex multi-function parts can sometimes be more difficult or expensive to manufacture than multiple simple parts. But in general, a thoughtful reduction in part count pays dividends in manufacturing efficiency.

2. Standardize Parts and Materials

Opt for off-the-shelf parts whenever possible to avoid reinventing the wheel with each new project. This streamlines your inventory management, cuts procurement costs, and ensures consistency in production. Reusing the same parts across multiple products also creates economies of scale. By avoiding custom-made components, you can eliminate the time and cost of tooling and setup.

We encourage our designers to start with standard parts and only move to custom solutions when absolutely necessary. It's also valuable to develop internal standards for commonly used components across product lines.

For materials, we default to widely available options that our manufacturing partners are experienced in working with. Uncommon materials may sometimes be necessary but often introduce additional cost and complexity.

3. Modular Design

Modular design involves creating independent subassemblies or modules that can be easily put together to form the final product. Imagine your product as a LEGO creation — a collection of individual bricks that come together to form a cohesive whole.

By breaking down your product into smaller, self-contained modules, you create a flexible system where each module can be manufactured and tested independently. Just like LEGO bricks, these modules can then be easily assembled and disassembled, allowing for customization, streamlined repairs, and faster upgrades without scrapping the entire product.

4. Ease of Fabrication

A core tenet of DFM is designing parts to be as easy to fabricate as possible using the available production processes. This may involve adding draft angles, adjusting wall thickness, or optimizing geometry for the specific manufacturing techniques you'll use, such as injection molding, sheet metal stamping, CNC machining, or 3D printing.

Whenever possible, choose fabrication methods that align with the capabilities of your manufacturing partners. Avoid pushing the boundaries too far beyond industry norms, as this increases risk and cost. Instead, aim for a design that plays to the strengths of the factory.

For example, if a client only produces a hundred devices a year, they might prefer we use sheet metal parts rather than invest in an expensive injection molding tool. Conversely, for clients producing thousands of units annually, injection molding becomes more cost-effective and allows for more complex surface development.

5. Optimize Assembly

While this principle starts to blur the line between DFM and DFA, it's a fundamental consideration to a future-proof design process. Assembly optimization includes:

- Designing parts that are easy to align and assemble from a single direction (ideally top-down)
- Using symmetrical parts to reduce orientation issues
- Incorporating self-locating features, such as tabs, slots, or grooves, to minimize handling
- Including self-fastening elements, such as snap fits or press fits, to eliminate the need for additional fasteners like screws or adhesives

- Minimizing the need for specialized tools to reduce tooling costs and improve production line flexibility

In a recent project for a self-checkout system, we asked the manufacturer for input during the design phase. During their review, they suggested several improvements, such as adding wire clips to manage cable routing. They also ran a mold flow analysis, which checks how plastic is injected to help prevent sink marks and warp. This feedback allowed us to update our files before investing in tooling, saving time and money.

6. Tolerances and Specifications

While it may be tempting to specify extremely tight tolerances everywhere, this level of precision is often unnecessary and expensive to achieve consistently. Instead, be judicious in how you apply tolerances to the design. Allow looser fits where possible and only tighten up on critical interfaces. This reduces rework and scrap rates while keeping costs under control.

We perform a tolerance analysis to check that parts will fit together correctly, even accounting for the worst-case scenarios of manufacturing variations. For instance, we might run an analysis to ensure that a plastic part coming out of a mold with a tolerance of plus or minus a few thousandths of an inch will still fit properly with other components without gaps or interference.

DFM Best Practices

Through decades of experience at StudioRed, we've developed a set of best practices that ensure the successful implementation of DFM principles:

- **Involve manufacturing partners early in the design process:** We often seek input from manufacturers before we even start designing. By involving them from the start, we can identify potential issues before they become costly problems. This collaboration helps us understand manufacturing constraints and gives us the opportunity to optimize designs for production.
- **Conduct DFM reviews at key milestones:** We hold regular DFM reviews throughout the design process. These reviews bring together designers, engineers, and manufacturing partners to evaluate the design from a manufacturability perspective.
- **Use DFM simulation tools to evaluate designs:** Modern CAD and simulation tools offer powerful capabilities for evaluating designs from a manufacturing perspective. At StudioRed, we regularly use tools for mold flow analysis, finite element analysis (FEA), and tolerance analysis.
- **Create prototypes to validate DFM decisions:** While simulation tools are incredibly useful, there's no substitute for physical prototypes when it comes to validating design decisions. We often create prototypes at various stages of the design process to test manufacturability, assembly processes, and overall product function.
- **Collaborate closely with suppliers:** Suppliers can and should be valuable partners in the DFM process. We tap into their

expertise on things like material selection, part geometry, and assembly methods to inform our design decisions.

Examples of Design for Manufacturing

Let’s examine some real-world Design for Manufacturing examples from our work at StudioRed. These illustrate how DFM principles can lead to significant improvements in product design and manufacturing.

Cable Box

In a project for a national cable company, StudioRed was tasked with designing a set-top box. During a design review, the manufacturer suggested we flip the printed circuit board (PCB) upside down to enable “in-process testing.” This meant testing could be done on the manufacturing line without additional fixtures, significantly reducing costs.

The change required about 30 hours of CAD rework but saved significant time and resources in the long run. Had this DFM input been received later in the process, the redesign effort would have been much greater.

Sheet Metal Assembly

In a sheet metal assembly project, StudioRed was faced with a decision on how to connect two parts to form a “T” shape. While screws, spot welding, or rivets were options, our partner, a major computer manufacturer, recommended something we hadn't considered — a toggle lock. This simple change, incorporated directly into the metal stamping process, proved more cost-effective than other joining methods and eliminated the need for additional assembly steps or equipment.

By collaborating with the manufacturer and leveraging their expertise, we avoided the need for new files, drawings, and potentially even additional prototype and testing rounds.

Small Wearable Device

A client approached StudioRed with the challenge of redesigning a wearable ring with embedded electronics. They had a very specific price point in mind and an ambitious production goal. Their existing ring design was expensive to manufacture and had a high failure rate due to tight tolerances and complex machining processes.

Recognizing the challenges of thin-walled, high-tolerance parts, we reached out to a partner specializing in hearing aid manufacturing. By collaborating with them, we were able to redesign the ring using two plastic parts plated in metal. This change improved the product's reliability and consistency while reducing costs by over 90%.

By applying DFM principles from the very beginning, we were able to develop a superior design that could be produced at scale while exceeding the client's target cost.

Streamline Your Product Development Process With DFM by StudioRed

Design for Manufacturing is about approaching product design with a deep understanding of manufacturing constraints and opportunities. At StudioRed, we've honed our DFM expertise through years of experience and a commitment to excellence. Our team of industrial designers and mechanical engineers collaborates closely with clients and trusted manufacturing partners to ensure every product we create is optimized for production from the very beginning.

Partner with StudioRed to transform your product development process. Contact us to learn how we can apply our DFM expertise to your next project.

FAQ

You might still have questions about how to implement Design for Manufacturability for your specific situation. Let's address a few common ones that come up in our discussions with clients and partners.

How Long Does DFM Take?

The DFM process is iterative and never truly "done" until you launch the product. However, the upfront DFM work typically takes a few weeks to a few months, depending on the size and complexity of the project. It’s tempting to rush through it or skip steps to save time, but it’s always worth investing the time upfront to avoid much costlier delays and re-spins later.

How Do You Start the DFM Process?

The first step in DFM is assembling a cross-functional team with representation from design, engineering, manufacturing, quality, supply chain, and other relevant areas. Then, you need to establish the key requirements and constraints for the product, such as target cost, annual volumes, and required materials and processes. This will guide the design effort and DFM analysis.

What’s the Difference Between Design for Manufacturing and Design for Assembly?

Design for Manufacturing and Design for Assembly are closely related but distinct disciplines. DFM focuses on optimizing the design of individual parts for fabrication, while DFA is about optimizing the design of the whole product for putting it together.

In practice, many of the same principles apply to both, such as reducing part count, using standardized components, and leveraging self-locating features. The key is to consider both DFM and DFA together in an integrated way to create a design that’s truly optimized for the entire manufacturing value chain.

Step 4: Testing and iteration

The penultimate step in the product design process focuses on testing and iteration.

Before you send the product off to be built or developed, it’s essential to test your prototypes, gather feedback, and address any usability issues or general design flaws.

The testing phase should involve real users (or test participants who closely represent your target users) and internal stakeholders.

Product testing and iteration usually encompasses:

- Usability testing—asking users to complete certain tasks with the product prototype and evaluating through observation/usability metrics (such as task completion time or error rate) how easy it is to interact with the product in its current form.

- Conducting user interviews to gather qualitative feedback on the product and identify areas for improvement.

- Conducting stakeholder interviews and design reviews to gather internal feedback on the design and ensure that the product aligns with business goals.

- Improving and updating product prototypes based on both user and stakeholder feedback.

Note that the product may go through several rounds of testing and iteration before it’s ready to be built. Once you’re confident that the product is functional, usable, and desirable—and that it’s feasible from a business perspective—you can take it forward for development.

Step 5: Development and launch

In the final stage of the product design process, product prototypes are handed over for development.

This step requires close collaboration with developers or manufacturers, depending on the nature of the product. The product designer shares all the technical specifications, documentation, and design assets necessary for bringing the product to life.

This is known as the “design handoff”, and it typically involves:

- Presenting final designs to key stakeholders, including developers/manufacturers.

- Compiling and sharing relevant design assets such as prototypes, style guides, and technical specs.

- Establishing a feedback loop between the design, development, and product teams.

Once the product has been built and quality assurance checks are complete, it’s ready for launch!

Medical Device Design and Development: Everything You Need To Know in 2024

Christian Bourgeois . July 18, 2024

While doctors and nurses are often the face of healthcare, behind the scenes, there’s a field that plays a vital role in advancing patient care: medical device design. This innovative discipline combines engineering, creativity, and medical knowledge to develop the tools and equipment healthcare professionals rely on every day to diagnose, treat, and monitor patients.

This post will break down what medical device design is and the key stages of the development process, from napkin sketch to FDA approval. Whether you’re a healthcare professional, an aspiring designer, or simply curious about the technology behind modern medicine, we’ll peel back the curtain on this fascinating intersection of healthcare and engineering.

What Is Medical Device Design?

Medical device design is the process of conceptualizing, developing, and refining diagnostic equipment, preventative devices, or instruments used to monitor or treat medical conditions. Medical devices range from simple tools like bandages to complex implantable devices like pacemakers.

Some popular types of medical products include:

-
  - **Diagnostic devices:** Used to detect or monitor medical conditions (e.g., X-ray machines, blood glucose meters, pregnancy tests)
  - **Therapeutic devices:** Designed to treat or manage medical conditions (e.g., insulin pumps, pacemakers, inhalers)
  - **Life-supporting or life-sustaining devices:** Essential for sustaining life or supporting vital functions (e.g., ventilators, dialysis machines, heart-lung machines)
  - **Surgical devices:** Instruments or tools for performing surgical procedures (e.g., scalpels, laparoscopic instruments, electrocautery devices)
  - **Implantable devices:** Surgically inserted into the body to replace, support, or enhance biological structures (e.g., artificial joints, stents, cochlear implants)
  - **Monitoring devices:** Track vital signs and other health parameters (e.g., blood pressure monitors, ECG machines, wearable fitness trackers)

- **Assistive devices:** Designed to aid individuals with disabilities (e.g., mobility scooters, hearing aids, screen readers)

Different types of medical devices are classified based on their function, intended use, and the risk they pose to patients. In the United States, the FDA categorizes medical devices into three classes: Class I (low risk), Class II (moderate risk), and Class III (high risk). This classification system determines the level of regulatory control and the approval process required for each device, with Class III devices undergoing the most stringent review before market authorization.

Stages of Medical Device Development

Medical device development is the process of transforming a concept into a commercially viable medical product. It's a structured process that typically involves several distinct stages.

1. Concept and Ideation

The initial stage of medical device product development begins with identifying an unmet medical need. This could stem from clinical observations, patient feedback, or gaps in existing healthcare practices. For example, a surgeon might struggle with a specific instrument, or a patient might find a particular medical procedure too invasive or uncomfortable. By pinpointing a specific issue, designers can target their efforts toward creating a meaningful solution through creativity and critical thinking.

Once they've identified the need, the next step is to generate ideas. This involves brainstorming sessions where no idea is too farfetched. The goal is to explore a wide range of possibilities without immediate judgment.

For example, imagine the identified need is helping individuals who suffer from a distorted sense of smell. Some brainstorming ideas might include a scent-neutralizing nasal spray, a smart air purifier that filters out specific odors, or an olfactory retraining app.

After brainstorming, it’s time to evaluate the feasibility of these concepts. This analysis considers technological capabilities, potential manufacturing processes, and initial regulatory considerations. Designers ask questions like:

- Can this idea be turned into a functional device?
- Is it cost-effective to produce?
- Will it comply with regulatory standards?

The outcome is a clear, well-defined concept that lays the foundation for subsequent development stages.

2. Design and Development

Once a viable concept is in place, the design and development phase begins. This involves detailed design and engineering to transform the initial idea into a functional prototype. Engineers work closely with designers and clinicians to create detailed design specifications, focusing on functionality and usability.

Medical device prototyping is a crucial part of design and development. Initial prototypes are developed and subjected to rigorous testing to evaluate their performance, safety, and durability.

For example, a prototype of a new insulin pump might be tested in a simulated environment to ensure it delivers the correct dosage, is resistant to water and impact, and maintains its functionality over extended periods. The goal is to identify potential issues early in development and refine the design accordingly.

This phase also includes the development of manufacturing processes. Engineers design the methods that will be used to produce the device, ensuring they are efficient, scalable, and capable of maintaining high-quality standards.

For instance, they may develop precise molding techniques for plastic components, optimize robotic assembly lines, or implement rigorous quality control checks at each stage of production. This preparation is essential for the next stage, where the device will undergo more extensive testing and regulatory scrutiny.

3. Verification and Validation

The goal of the verification and validation (V&V) stage is to ensure the medical device is safe, effective, and compliant with all regulatory standards. Verification confirms that the design meets the initial specifications and requirements, while validation shows that the final product meets the intended uses and user needs.

V&V typically includes clinical trials or evaluations. Here, the device undergoes rigorous testing in real-world scenarios to gather data on its performance, safety, and efficacy. This may involve collecting patient-reported outcomes, monitoring vital signs, assessing the device's impact on quality of life, and comparing it to existing treatments or standards of care. The objective is to demonstrate that the device performs as intended under actual conditions. This process also includes risk analysis, where developers identify potential hazards and mitigation strategies.

Regulatory standards and guidelines play a significant role during this stage. The device must comply with various regulatory requirements, which are often stringent and detailed. The specific requirements vary depending on the target market, as different countries and regions have their own regulatory bodies and standards.

For example, medical devices intended for sale in the United States must meet FDA regulations, while those sold in Europe must obtain a CE mark, which is a license to sell within the European Union. Engineers and regulatory experts work together to ensure all aspects of the design and development process align with these standards.

The final step is compiling documentation to obtain regulatory approval to market and sell the medical device. In the U.S., the FDA requires either premarket approval (PMA) for higher-risk devices or 510(k) clearance for moderate-risk devices with substantial equivalence to existing products. Approval depends on providing clinical evidence, test reports, risk analysis, and other data showing the device is safe and effective for the intended uses.

4. Production and Scaling

Once the device passes V&V, it's time to transition to full-scale production. This involves ensuring manufacturing processes are robust and scalable enough to produce the device efficiently and in large volumes.

The medical device development company will conduct small-scale production runs to validate processes before ramping up to higher volumes. This helps identify any issues to address and streamline the assembly line. Product samples are also tested again to ensure there are no deviations from the initial design.

Production teams implement stringent quality control measures to comply with Good Manufacturing Practices (GMP). This includes careful monitoring of the environment, equipment, packaging, storage, and distribution. Comprehensive documentation and standard operating procedures for each process are required. Products are closely inspected and tested at multiple points. Any non-conforming products are rejected to ensure patient safety.

Once the small-scale production runs are successful, the process scales by adding more resources and automation. However, quality cannot be compromised in favor of quantity. Additional quality checks are put in place to account for the higher output. This scaling process continues until the maximum production target is reached.

5. Post-Market Surveillance

The development journey doesn’t end with the product launch. Post-market surveillance is a continuous process of monitoring and improving the device’s performance in real-world settings.

This involves collecting feedback from healthcare professionals and patients, analyzing data on device usage and adverse events, and making necessary updates to ensure the device’s safety and effectiveness over time. Firms maintain regulatory compliance requirements through ongoing reporting and documentation.

As technology and clinical practice advance, the device may require updates to remain useful and safe. The manufacturer needs to plan for potential updates, recalls, and end-of-life strategies to properly phase out the device. An end-of-life plan helps ensure devices are replaced, serviced, or safely removed before they become obsolete or unsafe.

Key Considerations in Medical Product Design

Designing a successful medical device requires careful consideration of various factors that can significantly impact its performance, safety, and user acceptance.

- **Target user focus:** There is a natural tendency to develop a product that can do almost everything, with deep capability and often many, if not infinite, adjustments available. While it may not be what power users prefer, it’s important to simplify functionality to offer only what the majority of medical professionals or consumers will actually use.

- **Safety and robustness:** Incorporate both primary and redundant safety systems. Minimize or eliminate potential workarounds to prevent unintended use that could compromise safety. This can be as simple as designing a disposable unit to be unusable after the first time, thereby reducing the possibility of introducing potential contaminants into the system.
- **Ergonomics:** Conduct real-world testing with actual device form and size for hand-held devices. The StudioRed team once monitored multiple surgeries involving an arthroscopic wand and asked surgeons what they might suggest to improve or change. The common answer was, "It's fine." However, showing them mockups of various concepts they could hold and react to sparked detailed feedback.
- **Sustainability:** Disposability and eco-friendly design are valuable in medical device design. Doctors, nurses, technicians, and hospital buyers often respond to thoughtful medical equipment design solutions that consider these factors. Not only will this resonate in the sales cycle, but it will also likely become a point of pride for the hospital.

- **Compliance:** Consider the device's target countries and ensure compliance with relevant standards (e.g., UL, FDA, FCC, CSA, CE, RoHS). A safety consultant usually counsels the team during component selection, development, and testing.

- **Documentation:** Maintain detailed design history files throughout the development process, including emails, specifications, research, testing reports, and design files. It's important to keep files in chronological order to document the development process and rationale behind design choices.

The best medical device design companies maintain an internal copy of all file revisions. StudioRed has always followed this practice, and many clients return years later asking for a copy of the final design and engineering files.

Trusted Medical Device Design Solutions Since 1983

StudioRed has been a trusted name in medical device product design for over 40 years. Our expertise and dedication to excellence ensure that your medical device will meet all regulatory standards and user needs. Partner with us for your medical product design projects, and let's bring your innovative ideas to life.

Contact StudioRed today to learn more about our medical device design services and how we can help you succeed.

What Is New Product Introduction? + 6 Steps To Implement It

Christian Bourgeois . November 26, 2024

Quick Answer

New product introduction (NPI) refers to the process of bringing a new product to market, involving stages such as ideation, design, manufacturing, testing, and distribution.

If innovation is the key to success, new product introduction (NPI) is the roadmap. A well-executed NPI can drive revenue growth, enhance customer satisfaction, and solidify a company's competitive position.

From evaluating the latest design trends to crafting an effective pricing strategy, businesses must navigate a complex landscape to plan successful product introductions. We'll dive into the NPI process, discussing tips and best practices to ensure a smooth launch.

What Is New Product Introduction?

A new product introduction is the process of bringing a new product to market. It involves a series of stages, from ideation and product design to manufacturing, testing, and distribution.

Successful NPI requires careful planning and execution, including:

- Market research
- Product development
- Pricing strategy
- Marketing
- Sales

The New Product Introduction Process in 6 Steps

The NPI process involves several key stages that must be carefully executed to ensure a successful product launch. These steps include:

1. Ideation

The first step in the NPI process is ideation, where the initial spark of innovation ignites. This phase involves generating and exploring new product concepts that have the potential to meet customer needs and drive business growth.

Ideation sessions often bring together diverse teams, including:

- Engineers
- Designers
- Marketers
- Subject matter experts

Through brainstorming techniques like mind mapping and design thinking, teams can explore different product ideas that address their target market's pain points and needs. The goal is to generate a wide range of concepts before narrowing down to the most promising ones based on factors like customer demand and technical feasibility.

Example:

A consumer electronics company wants to introduce a new wearable device. During the ideation phase, the team brainstorms ideas such as a fitness tracker, a smartwatch, a health monitoring device, or a fashion accessory. They explore these possibilities to identify the most promising concept based on customer needs and feedback, market trends, and technical capabilities.

2. Market Research and Analysis

Once you've landed on a promising product concept, the next step is to delve into market research and analysis to validate your idea, understand customer needs, and identify potential competitors. Conducting thorough research lets you make informed decisions about product features, pricing, and marketing strategies.

Market research can involve multiple methods, including:

- **Surveys:** Collecting data through questionnaires or online surveys
- **Interviews:** One-on-one or group interviews with target customers or industry experts
- **Focus groups:** Small groups of participants interviewed together to discuss a specific topic
- **Observations:** Observing customer behavior in natural settings
- **Ethnography:** Immersion in the target market to understand their culture and behaviors
- **Competitive and market analysis:** Analyzing industry data, market trends, and competitor information
- **Data mining:** Analyzing large datasets to identify patterns and trends
- **Social media listening:** Monitoring social media platforms to understand customer sentiment and discussions
- **Online communities:** Engaging with online communities relevant to the target market
- **Customer segmentation:** Dividing target markets into smaller, more manageable groups based on specific characteristics like age, lifestyle, and occupation, enabling teams to tailor product offerings and marketing strategies to meet the unique needs and preferences of each segment

By combining different research methods, you can gain a comprehensive understanding of your target market.

Example:

The consumer electronics team conducts market research to support the wearable device concept. They survey potential customers to determine their preferences for features, design, and price.

They also analyze the competitive landscape to identify existing wearable devices, their strengths and weaknesses, and their market share. This research helps the team refine the product concept, set appropriate pricing, and develop effective marketing strategies.

3. Design and Prototyping

With a solid understanding of your target market and product concept, you're ready to bring your vision to life through design and prototyping. This phase involves:

- Translating your ideas into tangible products
- Creating detailed specifications and product requirements
- Building prototypes to test and refine your design

The building process involves multiple stages that serve distinct purposes. Low-fidelity prototypes allow for initial exploration, like testing core concepts and user flows, so you can iterate on ideas at a low cost. As you get closer to the final version, you'll create high-fidelity versions for a more realistic representation of the final product and to gain approval from stakeholders.

Your design and engineering team will work together to create blueprints, schematics, and other technical documents to define the product's:

- Scale
- Materials

- Functionality
- User interface

The design and engineering teams is then tasked with building a prototype to test the design's feasibility, functionality, and user experience. This is an iterative process that requires building and testing multiple prototypes to identify and address any issues before moving to production.

Example:

The design team creates detailed specifications for the wearable device, including things like the dimensions of the user interface and the materials of the band. They design the device's hardware and software components.

The design team passes the specifications to the engineering team to create a prototype that will be used to test the device's functionality, comfort, and battery life during the testing phase.

4. Design Validation and Testing

After designing and prototyping your product, it's important to validate the data and conduct thorough testing to make sure it meets your — and your target market's — specifications and desired performance.

Data validation involves checking the accuracy and consistency of the data collected during development. You'll need to verify:

- Product requirements
- Measurements

- Calculations
- Simulations

Testing, on the other hand, subjects the product to various scenarios and conditions to assess its performance, reliability, and durability. This may include:

- Functional testing
- Stress testing
- Environmental testing
- User testing

After internal testing, you can choose to conduct beta testing or pilot programs with potential customers. This process lets you gather real-world feedback and identify any issues or areas for improvement before launching the product to the wider market.

Once you receive feedback, you can refine the product to better meet user expectations, market demands, and regulatory requirements. This iterative cycle ensures you address as many critical aspects of your product as possible before proceeding with full-scale production, helping reduce the risk of costly post-launch modifications.

Example:

The product team checks the prototype and verifies that all the numbers and calculations are correct. They also conduct various tests, such as stress tests to ensure the device can withstand extreme temperatures and usage, environmental tests to assess its performance in different conditions, and user acceptance testing to gather feedback from potential users.

Once the product has passed internal testing, the team asks potential users to try the device and give their feedback. This can help identify any problems and ensure the device works as it should.

5. Pre-Production to Mass Production

If your product passes rigorous testing and validation, you've got the green light to transition from pre-production to mass production. In this step, you'll:

- Finalize production plans
- Establish manufacturing processes
- Select manufacturing partners
- Procure the necessary materials and equipment

Once these preparations are complete, you can begin scaling up production to meet market demand.

Example:

For the wearable device, the team finalizes production plans, selects manufacturing partners, and establishes quality control procedures. They also acquire all the necessary components, batteries, and packaging they'll need to get their new product on the shelves.

6. Launch and Post-Launch Evaluation

It's time for your marketing team to shine in the final step of the NPI process. The launch phase relies heavily on factors like:

- Advertising
- Sales

- Content marketing
- Social media marketing
- Influencer partnerships
- Word of mouth
- Retail distribution

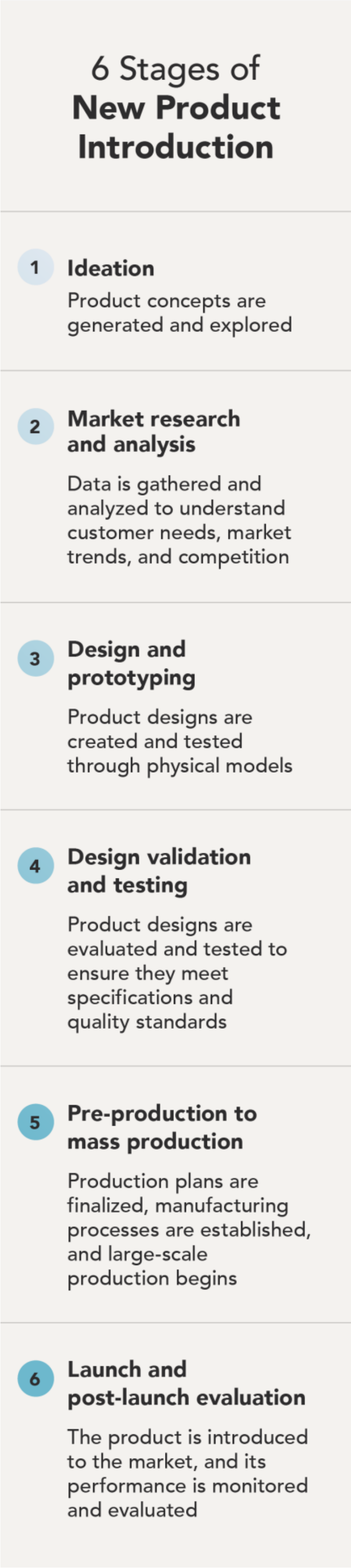
Make sure you have a well-crafted launch plan that outlines your marketing and sales strategies, target audience, and key messages before you go to market. After your initial launch, continue monitoring sales performance and customer feedback for an idea of what's working and what's not.

By continuously gathering and analyzing customer feedback and reviews, you can gain valuable insights into product performance, pinpoint opportunities for improvement, and ensure your offerings remain relevant and competitive. You'll likely need to tweak your marketing approach to cater to changing customer preferences.

Example:

The wearable device product team launches a marketing campaign to create awareness and generate interest among their target audience before distributing the device through retail channels and online stores.

After the launch, the team monitors sales figures, tracks customer reviews, and gathers feedback through surveys. This data helps them determine what factors need to be tweaked to see optimal results.



6 Stages of **New Product Introduction**

1. **Ideation**
   Product concepts are generated and explored
2. **Market research and analysis**
   Data is gathered and analyzed to understand customer needs, market trends, and competition
3. **Design and prototyping**
   Product designs are created and tested through physical models
4. **Design validation and testing**
   Product designs are evaluated and tested to ensure they meet specifications and quality standards
5. **Pre-production to mass production**
   Production plans are finalized, manufacturing processes are established, and large-scale production begins
6. **Launch and post-launch evaluation**
   The product is introduced to the market, and its performance is monitored and evaluated

Why Is NPI Important?

New product introduction is a crucial process for businesses seeking to thrive in today's competitive market. By effectively introducing new products, companies can:

- **Gain a competitive advantage:** NPI allows businesses to stand out from competitors, offer unique solutions, and capture market share.
- **Meet customer needs:** By developing products that address customer pain points and desires, companies can build a loyal fan base. This leads to more sales, a bigger market share, and long-term success.
- **Drive business growth:** NPI can pump up revenue by introducing new products that tap into untapped markets or address unmet customer needs. Successful launches can create excitement and attract new customers, helping your business grow.
- **Enhance brand reputation:** Introducing innovative and high-quality products can enhance a company's brand reputation. Happy customers and successful launches build trust, loyalty, and brand awareness.
- **Facilitate innovation:** NPI encourages a culture of innovation and creativity within an organization. By continuously developing new products, companies can stay ahead of the competition, adapt to changing market trends, and foster a culture of innovation.

StudioRed can guide you through the entire product development journey, from concept to launch. Our team of experts delivers tailored NPI solutions that help you bring innovative products to life.

Contact StudioRed today to start shaping your vision into reality.

FAQ

Have questions about NPI? We've compiled a list of frequently asked questions to help you understand the process and overcome common challenges.

What Is NPI in Engineering?

New product introduction in engineering is the process of turning a product vision into a tangible product. It involves several steps, including:

- Product ideation and concept development
- Market research and analysis
- Design and prototyping
- Engineering and technical development
- Manufacturing and production
- Testing and quality control
- Launch and post-launch evaluation

NPI is essential for engineering teams looking to create cutting-edge products that resonate with customers and boost the bottom line.

What Challenges Do Companies Face During New Product Introduction?

Companies often encounter several challenges during new product introduction, like:

- **Market uncertainty:** Identifying the right market fit, understanding customer needs, and predicting market trends can be challenging.
- **Resource constraints:** Limited budget, time, and personnel can slow down product development and launch.
- **Technical difficulties:** Engineering challenges, design flaws, or supply chain disruptions can delay product development and increase costs.
- **Competitive pressure:** Fierce competition can make it difficult to differentiate new products and gain market share.
- **Regulatory compliance:** Adhering to industry regulations, safety standards, and environmental requirements can be complex and time-consuming.
- **Risk management:** Managing risks associated with product development, manufacturing, and market introduction is crucial but can be tricky.
- **Customer acceptance:** Getting customers to embrace a new product can be tough, especially if it involves a big change in behavior or technology.

4. Beyond the product design process: What happens next?

We’ve set out a linear product design process with a seemingly clear-cut end point. But, in reality, the product design process is ongoing. Once the product has been built and launched, the product designer will continue to monitor and iterate on the product.

They might run A/B tests to compare different versions of certain features and conduct ongoing usability tests to improve the user experience. They will also monitor the target market to identify new opportunities to deliver additional end-user and business value.

A successful product isn’t static. It must evolve in line with the market and continuously adapt to the target users’ needs. As such, the product design process is never really finished.

5. Key takeaways

The product design process is, at its core, a problem-solving endeavor. It’s about understanding the challenges your target users face and coming up with effective solutions—then designing those solutions to ensure that they’re desirable, usable, and accessible.

At the same time, the product design process seeks to balance user needs against business goals. The most effective products don’t only deliver value to the end user; they also help to drive business growth and achieve strategic objectives.

And, while the product design process is highly adaptable, every successful product is rooted in continuous research, ideation, design, testing, and iteration. You can't build an effective product without those steps!

Engineering Design Process: 7 Steps To Optimize Your Design

Christian Bourgeois . December 23, 2024

The engineering design process (EDP) is a method of collaboration that allows teams to design, build, and test new products or systems.

How do engineers turn a mere concept into a tangible reality? The answer lies in the engineering design process (EDP).

The engineering design process guides engineers and developers in generating various ideas and solutions and testing their potential. As an iterative process, this method is a useful strategy to create refined market solutions that excel in user experience.

This article will break down the engineering design process and discuss best practices for implementation.

Key takeaways:

- The engineering design process helps engineers break down problems into manageable components, identify potential solutions, and develop innovative designs.
- The EDP’s cyclical approach allows engineers to learn from their concepts, improve their designs, and ultimately create optimal solutions.
- By understanding and utilizing this process, teams can approach problem-solving more systematically and creatively.

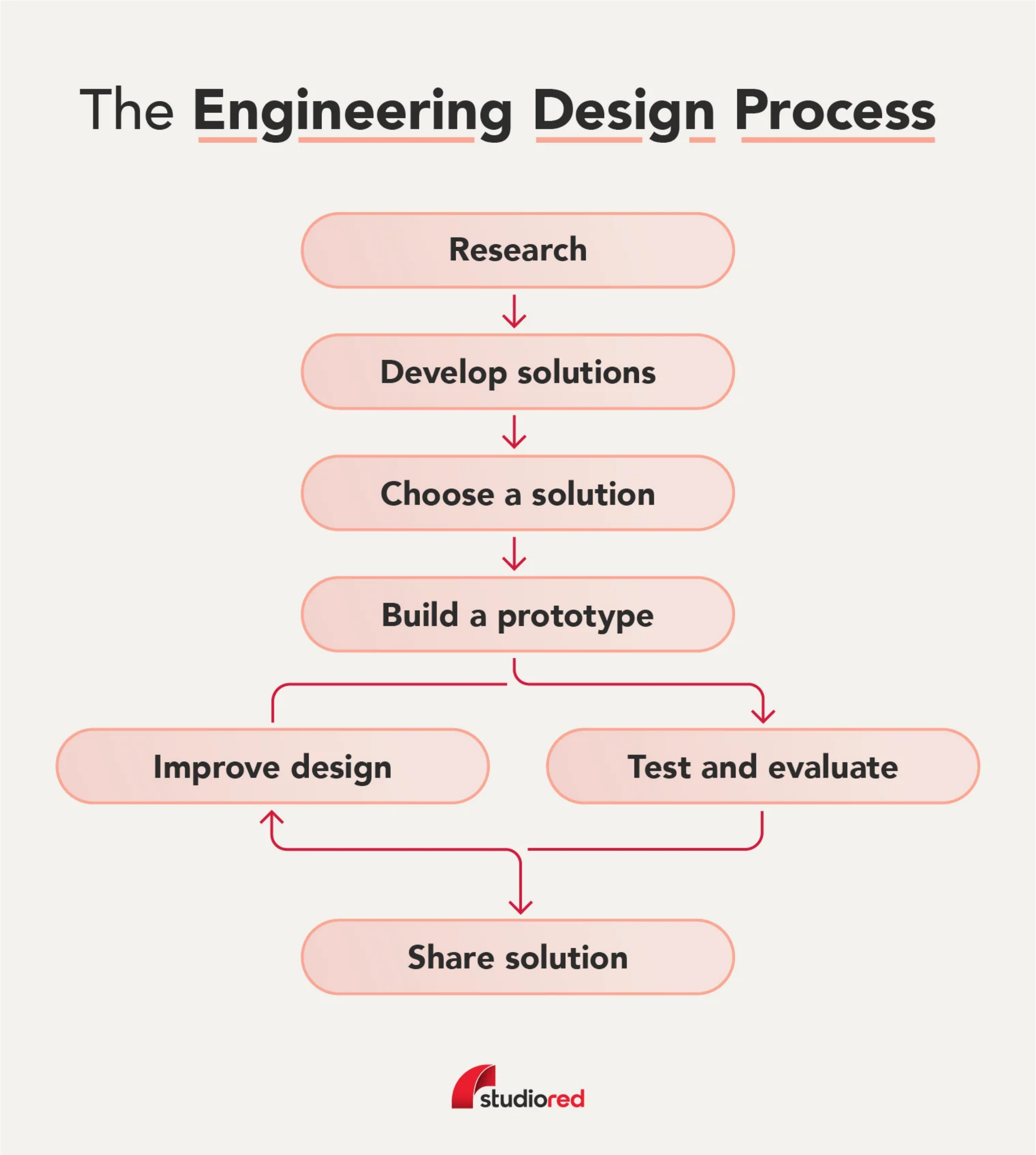
What Is the Engineering Design Process?

The engineering design process is a framework for teams to solve problems. It outlines how engineering teams identify a problem, brainstorm solutions, and test ideas and theories. The process is defined yet flexible, meaning teams can adjust goals, ideas, and solutions as they go.

The EDP is a creative and cyclical process where engineering teams collaborate to generate ideas, work together to plan execution, and make, test, and improve on the solutions generated.

8 Steps of the Engineering Design Process

The EDP steps outlined below provide a structured approach to improve team collaboration, and streamline product or system development and design.


The Engineering Design Process
Research
Develop solutions
Choose a solution
Build a prototype
Improve design
Test and evaluate
Share solution
studiored

1. Identify the problem

This first step requires your team to identify the problem that needs a solution. This could include analyzing feedback from users or field specialists, surveying a market sector, or internally assessing the effectiveness of an existing product or system.

The engineering design process applies to electrical, mechanical, and civil design challenges. It is also central to product design, as it creates a path toward continual improvement and innovation. The EDP can also be used to improve existing systems, making it valuable in manufacturing process design and quality control systems.

Example:

A beverage manufacturer may receive complaints from consumers about leaks and explosions when their beverages are placed in certain environments, a clear indicator that there's room for improvement in their beverage carton design.

2. Research the problem

Proper research is a critical step in the engineering design process, as it informs your team's problem-solving focus and design strategies. Part of the research can include market analysis to determine how a potential solution will be competitive and align with current industry trends.

Thorough research will also help identify the urgency of a solution, such as falling market share or current product development among competitors. This information can set the timeline for a speed-to-market solution.

If your team has identified an industry-wide problem, then the solution developed could become a widely applicable new standard.

Example:

Market research may reveal common complaints stemming from one beverage manufacturer, or maybe they're focused on a single type of carton or beverage. The team could also conduct store checks to assess the condition of products on shelves or examine how competitors are packaging their products to identify potential weaknesses in their current packaging design or manufacturing process.

This is also a great time to create a product requirements document (PRD), outlining the product's purpose, target market, competition, and other important details.

3. Develop Possible Solutions

Brainstorming allows engineering knowledge, technical skills, and creativity to contribute to innovative solutions. Working from the problem identified and the completed research, teams can use this step as an open forum to capture ideas.

Example:

Your team is challenged with finding a solution to the integrity of carton lining in uncontrolled environments. Possible solutions could surround packaging design, manufacturing processes, chemical treatments, or material selections. This step gives subject matter experts (SMEs) the space to propose solutions and get input from the team before moving forward.

4. Find the Best Solution

Next, your team can evaluate the ideas generated and identify the best solution to develop. Working together, the team can assess:

- How well the solution solves the problem
- If it is technically feasible
- The cost implications
- Any production challenges, such as the need to change equipment

A review of the research will also inform the team if the solution solves any additional issues or impacts currently well-performing aspects of a product.

Example:

When solving the beverage carton problem, your team may have generated several concepts, from design adjustments to changes in the carton materials. Selecting the best solution would involve addressing regulatory requirements, logistics, production, and costs across a global supply chain. You can also add this information to the PRD you created in step 2.

5. Create a Prototype

The prototype stage of the EDP is where your team's technical skills are used to model a solution. This can include creating sketches, CAD, or other types of information-rich design plans that can be converted into 3D models and renderings. The prototype captures the most viable solution generated by the team in the previous steps of the engineering design process.

Example:

Once the beverage carton team has designed a prototype, it can be put proto-fabricated and prepared for the next steps of the process. Regardless of the type of prototype, its value comes from the feedback gained, which the team can then incorporate into final product development.

6. Test and Evaluate

When a team follows the engineering design process, the intention is to solve a problem. This stage of the EDP is where the team can test their solution to verify its effectiveness. It's also an opportunity to test the prototype against existing performance metrics to see if the new model has any negative impacts.

Example:

In the beverage carton example, testing prototypes in different temperatures and affecting settings like humidity would be important data to gather.

7. Improve the Design

The iterative nature of the engineering design process allows teams to evaluate their progress and refine the solution. The testing stage of the EDP can help inform teams of unforeseen problems with a prototype. In some instances, this can help the team adjust the design, or it may mean that a new solution is needed.

Where a prototype fails, the team can return to earlier steps in the EDP, revisit their research, and work through the process again.

Example:

If your team proposed to change a carton material but did not adjust the assembly process, one or both of these issues may need to be resolved before reaching a final solution.

8. Communicate results

As teams move through the engineering design process, it's important to capture notes and information that can be organized and communicated. This step not only conveys the current solution to product development teams but it can inform other product design teams. Communicating the results of the process can contribute to market-wide safety or quality control improvements.

Example:

If the beverage carton prototype replaced a plastic with a metal, this would have implications for cooking. This type of information would be crucial to the product development team so they can carry this throughout the product lifecycle to the end user.

Best Practices for Implementing the Engineering Design Process

The engineering design process works most effectively when the team implements the intention behind each step. These best practices span industries and applications as a clear framework for teams to work within the engineering design cycle.

- **Set a clear goal:** Start with a well-defined problem to solve that has a specific market impact.
- **Iterate and revise:** Expect a trial-and-error process that produces several versions of a solution.
- **Gain diverse input:** Listen to technical experts, users, and other stakeholders such as client account managers.
- **Capture the process:** Document the process in full to capture lessons learned, which can inform future design iterations and improve overall efficiency.
- **Embrace prototypes:** Implement models to prove the success or failure of potential solutions through user feedback.
- **Test and get feedback:** Conduct rigorous testing to identify and address potential issues early in the design process. Incorporate user feedback to refine the design and ensure it meets the target audience’s needs.
- **Set success metrics:** Establish clear, measurable criteria to evaluate the effectiveness of potential solutions.
- **Define design:** Provide detailed design instructions for the product development team to carry forward.

Take a Systematic Approach Toward Innovation

The engineering design process is about collaboration, communication, and innovation. It is a proven method for aligning teams toward clear goals that deliver for clients and users.

DESIGN PROCESS

THE SUCCESS OF A PROJECT DEPENDS ON HAVING AN EFFECTIVE PROCESS IN PLACE

We are passionate about our work and about teaching conceptual illustration and design for the transportation industry (utility, recreational and military vehicles) and related products (helmets and other accessories). We like to apply our knowledge to different types of products. We believe that "Everything that deserves to be made deserves to be made well."

1. Preliminary research

- Index of competitors and strategic positioning
- Direct and indirect market trends and competition
- Analysis of existing products and activity analysis in the field (observation of users and operators)
- Analysis and portrayal of the typical buyer (lifestyle)
- Historical visual analysis of the client company's products (DNA history)
- Creation of visual cues (features) unique to the client brand (DNA application)
- Visual guide for style development in conjunction with engineering, marketing, and design objectives (product positioning and mood boards)
- Proximity-based styling and design analysis (as per Scott Robertson's theory (ACCD)

2. Preliminary layouts, ideation – human factors & ergonomics (HF&E)

3. 2D-3D renderings, vehicle architecture's layout

4. Digitization (scan) 3D reference/benchmarking

5. CAD preliminary surfaces

6. Small-scale or full-size clay models

7. Clay model 3D scanning

8. Final “Class A” CAD surfaces

9. Graphic design, paint scheme

10. Follow-up

QUALITY

Fast service, quality, feasibility, experience, imagination, precision, attention to detail, on-time delivery, attention to client needs, access to private specialized documents on industrial design and transportation. If needed, The Creative Unit, known for its passion for industrial design, can work with an extensive network of loyal partners who are all equally enthusiastic about their craft, who love creating, developing, and completing a project, and who value talent.

WHAT IS INDUSTRIAL DESIGN ?

Industrial design

is a creative activity that aims to determine the formal properties of industrially produced objects. This includes external features (style), but primarily the structural and functional relationships that give an object a consistent unit, both from the manufacturer's and the user's point of view. (ICSID)

Industrial design

is a combination of applied art and applied science, whereby the aesthetics, ergonomics and usability of products may be improved for marketability and production. The role of an industrial designer is to create and execute design solutions towards problems of form, usability, physical ergonomics, marketing, brand development and sales. IDSA – Industrial Designers Society of America

Industrial design

is also a creative activity whose will is to establish the qualities multifaceted objects, processes, services and systems in life cycles complete. The design has to do with products, services and systems conceived with tools, organizations and logic contributed by the industrialization (not only in the case of serialized processes). International Council of Societies of Industrial Design (lCSlD)

The World Design Organization (WDO)™, formerly the International Council of Societies of Industrial Design (Icsid), is an international non-governmental organization founded in 1957 to promote the profession of industrial design.

The World Design Organization (WDO)™, formerly known as the International Council of Societies of Industrial Design (Icsid), is an international non-governmental organization that promotes the profession of industrial design and its ability to generate better products, systems, services, and experiences; better business and industry; and ultimately a better environment and society.

From 12 founding professional design associations in 1957, WDO has grown to include over 170 member organizations from more than 40 nations, engaging them in collaborative efforts and providing them with the opportunity to be heard internationally.

A renewed vision and mission was approved by the members at the general assembly in October 2015 along with an approval to change the name of the organization to World Design Organization.

WDO has United Nations Special Consultative Status.

LAND ACKNOWLEDGMENT

Based in Montréal (Canada) since 2005, World Design Organization acknowledges that its Secretariat is located on the unceded Indigenous territory of the Kanien’kehá:ka. For centuries, these lands have served as a traditional gathering place for many nations and WDO honours the Indigenous leadership and knowledge that continues to shape this territory, and others around the world in which we work.

For over 65 years, WDO has gathered design organizations and designers they represent into a global community. Today, we support a growing network of over 200 WDO Members and are the only organization connecting corporate, educational, professional, promotional and municipal design institutions.

Our global community recognizes the power of design-led transformation. Together, we work to advance the profession of industrial design and promote its contribution to economic, social, cultural and environmental development. Through collaboration, exchange and partnership, we invite you to join us as we work to design our way to a better world.

On **2 November 2021**, the WDO Foundation™ was established to further the organization’s mission of improving global quality of life through design. Engaging with educational institutions, industry, and global non-governmental organizations, the WDO Foundation will develop partnerships in technology, research and development and sustainability to support a variety of design-led projects and programmes.

As an international organization, WDO and the WDO Foundation are committed to leveraging their position to support the profession of design and its role in building a more equitable and sustainable world. The establishment of this foundation represents an important next step for WDO in expanding the scope and impact of our global activities.

Alongside its partners, the WDO Foundation works to:

- support the development of design students and professionals by funding quality educational programmes, grants and scholarships that emphasize and facilitate interaction, collaboration and partnership across international communities;
- raise awareness and demonstrate the benefits and tangible outcomes of design-led programmes to solve local and global, social and environmental issues;
- provide stakeholders from the civil society, industry, governmental and non-governmental organizations with support from the design community;
- support and fund educational endeavors and community projects to explore design innovation as a means to improve the well-being of communities.

THE CREATIVE UNIT INC. 2004-2024 / 20 YEARS OF INDUSTRIAL DESIGN AND TRANSPORTATION DESIGN / MARTIN AUBÉ, BDI, BA, ADIQ, IDSA, 36 YEARS OF INDUSTRIAL DESIGN AND TRANSPORTATION DESIGN

“Between two products equal in price, function and quality, the one with the most attractive exterior will win.” Raymond Loewy

“What is worth doing, is worth doing well.” Nicolas Poussin

“The first quality of style is clarity.” Aristotle

“Fashion fades, only style remains.” Coco Chanel

“Talent is the ability to focus on one or another object and see something new, something that others do not see.” Leo Tolstoy

“Who thinks little is mistaken much.” Leonardo da Vinci

“Imagination rules the world.” Napoléon Bonaparte

“Discipline equals freedom.” Jocko Willink

“Beauty is only a simulacrum, youth is only a lure”. Gotlieb

TO IDEATE & IMAGINEER

IN THE DESIGN PROCESS

Ideation is the creative process of generating, developing, and communicating new ideas, where an idea is understood as a basic unit of thought that can be either visual, concrete, or abstract.[1] Ideation comprises all stages of a thought cycle, from innovation, to development, to actualization.[2] Ideation can be conducted by individuals, organizations, or crowds. As such, it is an essential part of the design process, both in education and practice.[3][4].

Criticism

The word "ideation" has come under informal criticism as being a term of meaningless jargon.

The term "Imagineering", a portmanteau, was introduced in the 1940s by Alcoa to describe its blending of imagination and engineering, and used by Union Carbide in an in-house magazine in 1957, with an article by Richard F. Sailer called "BRAINSTORMING IS IMAGination engINEERING". Disney filed for a trademark for the term in 1989, claiming first use of the term in 1962. Imagineering is a registered trademark of Disney Enterprises, Inc.[4].

Both terms describe the CREATIVE PROCESS.

Creativity is a cornerstone of human evolution and is typically defined as the multifaceted ability to produce novel and useful artifacts. Although much research has focused on divergent thinking, growing evidence underscores the importance of perceptual processing in fostering creativity, particularly through perceptual flexibility. The present work aims to offer a framework that relates creativity to perception, showing how sensory affordances, especially in ambiguous stimuli, can contribute to the generation of novel ideas. In doing so, we contextualize the phenomenon of pareidolia, which involves seeing familiar patterns in noisy or ambiguous stimuli, as a key perceptual mechanism of idea generation—one of the central stages of the creative process. We introduce “divergent perception” to describe the process by which individuals actively engage with the perceptual affordances provided by ambiguous sensory information, and illustrate how this concept could account for the heightened creativity observed in psychedelic and psychotic states. Moreover, we explore how divergent perception relates to cognitive mechanisms crucial in creative thinking, particularly focusing on the role of attention. Finally, we discuss future paths for the exploration of divergent perception, including targeted manipulation of stimulus characteristics and the investigation of the intricate interplay between bottom-up and top-down cognitive processes.

The CREATIVE PROCESS in INDUSTRIAL DESIGN ENGINEERING for Products and Transportation

Creativity is the ability to produce or develop original work, theories, techniques, or thoughts. A creative individual typically displays originality, imagination, and expressiveness.

Creative thinking refers to the mental processes leading to a new invention or solution to a problem. Products of creative thinking include new machines, social ideas, scientific theories, artistic works, and more.

Imagination is the ability to mentally simulate situations and ideas not perceived by the physical senses – lays the foundation for creativity. Yet imagination alone is insufficient to produce creativity. We define two types of imagination important for creativity: social-emotional and temporal.

Social-emotional imagination is the ability to conceive of and reflect on multiple social perspectives and scenarios and the implications of these for one’s own and others’ lives. It promotes creativity by helping individuals understand multiplicities of identity and experience within themselves and others, reason ethically, and appreciate human diversity and potential.

Temporal imagination is the ability to engage in mental time travel, counterfactual thinking, and mind-wandering. It can lead to creativity by allowing individuals to engage in the kind of nonliteral, divergent, and future-oriented thought creativity necessitates.

For creativity to happen, imaginative thought is infused into mental simulations that are regulated, evaluated, and integrated to conjure new ideas and concepts. As such, in the brain, creativity relies heavily on the default mode network, which is known to be involved in mental simulations across time and especially about social content.

Creativity also relies on organized interactions between the default mode network and the executive attention and salience networks, in order for imaginings to be strategically organized into coherent, meaningful plans and actionable ideas. To harness the potential of imagination, individuals need conducive personal qualities, including openness to experience and intrinsic motivation, as well as a supportive context.

Creativity and Imagination

Creativity is defined by psychological scientists as the generation of ideas or products that are both original and valuable. Creativity relies on imagination, the conscious representation of what is not immediately present to the senses. Although research on creativity has increased in quantity and quality since J. P. Guilford’s presidential address to the American Psychological Association in 1950, this fundamental human ability remains understudied in comparison to other important psychological phenomena. We are currently conducting a number of different research projects designed to better understand the causes and consequences of creativity, as well as how to enhance it.

Motivation and Creativity

One important antecedent of creative behavior is motivation. Why do individuals engage in creative work? What benefits, if any, do they anticipate? Past research on this important topic has shown that individuals who are intrinsically motivated tend to be more creative. In other words, individuals who engage in creative activities for the sake of the activities themselves (and not for the sake of extrinsic constraints of rewards) are better able to come up with original and valuable ideas. In addition, a small but growing body of literature suggests that prosocial motivation, defined as the desire to contribute to the lives of others, may also enhance creative thinking. Our ongoing research projects attempt to broaden the scientific understanding of the role of motivation in creativity by further investigating the specific nature of creators' motivations, and the relationship between motivations, achievement, and well-being.

Creativity and Well-Being

Past research suggests that creative activities may have therapeutic benefits and enhance well-being. To date, little research has however investigated the mechanisms explaining how creative thinking may confer its benefits. Current research projects at our center examine the possibility that creative thinking may enhance well-being by enhancing cognitive flexibility and problem-solving abilities, by providing individuals with an important sense of mastery and agency, and by helping individuals perceive benefits after going through adversity.

Creative imagination

"Creative imagination" is what we normally consider to be creativity with a large C – composing an opera or discovering something groundbreaking. This is different from everyday creativity, such as coming up with imaginative solutions to household problems or making crafts.

Creative inspiration is notoriously elusive. Being able to train creativity or induce a state of creativity has therefore long been the aim of many artists and scientists.

Research has suggested that creative imagination can also be boosted through our environment or simply putting in lots of hard work. For example, experimental studies have shown that when children engage with creative content or watch others be highly creative, they become more creative themselves.

There are two phases to creative imagination. “Divergent thinking” is the ability to think of a wide variety of ideas, all somehow connected to a main problem or topic. It tends to be supported by intuitive thinking, which is fast and automatic. You then need “convergent thinking” to help you evaluate the ideas for usefulness within the main problem or topic. This process is supported by analytical thinking – which is slow and deliberate – allowing us to select the right idea.

So if you want to design that masterpiece, having lots of brainstorming sessions with friends may help you come up with new ideas.

Research suggests that the first requirement is actually exposure and experience. The longer you have worked and thought in a field and learned about a matter – and importantly, dared to make many mistakes – the better you are at intuitively coming up with ideas and analytically selecting the right one.

The best preparation for the future is paradoxically to imagine the process – not the outcome – of your desired future event.

We all have imaginative ability to various degrees, and it’s difficult to imagine where humankind would be without it. So even though you are yet to actually write that novel you’ve got in you somewhere, keep trying. There are many routes to boost creativity, with play, practice, and experience being crucial. It may even make you smarter.

As Einstein himself reportedly once said: “The true sign of intelligence is not knowledge but imagination.”

UNLOCKING THE POWER OF THE MIND: THE BRAIN REGION BEHIND CREATIVITY AND IMAGINATION

Last updated: February 7, 2024

Most of us think about creativity and imagination in relation to the arts, such as writing, theater, or fine art. However, creativity and imagination play a role in virtually all vocations and hobbies. The two terms aren't synonymous, even if they do often get mentioned in tandem. Imagination involves simulating mental pictures, new ideas and concepts, and sensations without input from the senses. Creativity, on the other hand, involves taking those visualizations and turning them into something new. Both imagination and creativity are essential to problem-solving and finding workarounds for difficult situations. These traits are helpful in everything from software development to customer service. But have you ever considered what part of the brain is responsible for creativity and imagination?

WHAT PART OF THE BRAIN CONTROLS CREATIVITY AND IMAGINATION?

The answer to "what part of the brain controls creativity and imagination" is as complex as the brain itself. No single area of the brain is solely responsible. Instead, there are several regions of the brain that contribute to what we call imagination and creativity. Among these are the following:

The Prefrontal Cortex

The prefrontal cortex is the part of the brain that handles higher cognitive activity, such as making decisions and solving problems. Relatively recent research shows a link between the prefrontal cortex and creativity. In addition, a part of the prefrontal cortex called the ventromedial prefrontal cortex (VMPFC), is charged with regulating emotions and self-reflection, both of which spur the creative process.

The Limbic System

The limbic system is a collection of brain structures located next to the thalamus and underneath the cerebral cortex. These structures help to control our emotions and our motivations. The hippocampus and amygdala, both parts of this system, are especially relevant to creativity and imagination. The hippocampus is charged with storing and retrieving memories, and the amygdala is responsible for processing emotions. In conjunction, these two parts of the brain help to form ideas.

The Parietal and Occipital Lobes

When you imagine what something or someone might look like (even if you've never seen it or them), that's your parietal and occipital lobes at work. These two parts of the brain are responsible for spatial orientation and visual processing. It is also widely believed that mental images and ideas are formed in these two areas.

Neuroplasticity and Creativity

Neuroplasticity refers to the brain's ability to "re-wire" itself and thus change the way you view the world around you. In essence, you can teach yourself to be more creative. Neuroplasticity is how the brain heals after a traumatic brain injury or stroke. It's also behind how we learn and retain new skills.

According to the tenets of psychology, creativity comes from divergent thinking. Divergent thinking is when we think laterally, which means thinking of various possible outcomes, solutions, or scenarios, not just the most expected one. Children are experts at divergent thinking (and, therefore, often more creative), since they don't know what the most likely solution is to a given situation and, therefore, must consider all possible solutions.

The good news is that divergent thinking – and thus creativity – can be taught. Several techniques can boost your ability to think creatively. For example, take two unrelated objects, such as a car key and a thimble, and spend five minutes thinking about their possible associations. Another exercise involves thinking about alternative uses for everyday objects – like The Little Mermaid's Ariel combing her hair with a fork.
Lastly, you can practice the SCAMPER technique. This psychological exercise is used for brainstorming and generating ideas. SCAMPER is an acronym for:

- Substitute – What can you change in a given situation?
- Combine – Does combining elements help the situation?
- Adapt – What existing element can you repurpose?
- Modify – What can you change?
- Put to another use – Should you use the project in another way?
- Eliminate – What do you need to get rid of?
- Reverse – Do you need to look at the situation from another point of view?

IMPROVING CREATIVITY AND IMAGINATION

It's a myth that your creativity and imagination are innate from birth. You can improve both in several ways, no matter your age. Some of these methods include:

Meditation

Meditation can help you clear your mind so that you're more receptive to divergent thinking and less consumed by the distracting minutiae of the average day.

Visualization

Visualization is a part of divergent thinking. Actively practice envisioning different solutions and scenarios to make your mind more flexible and used to creativity.

Mind Mapping

Mind mapping involves putting down on paper the flow of possible solutions to a given situation. Sometimes, seeing something on paper aids in the overall visualization process.

Your Environment

It's also helpful to set up an environment that encourages creativity. For example, look at how children's playrooms have toys, posters, and art supplies to help the children explore their creativity. Adults can set up a similar environment, perhaps by a window with a scenic view, with creative elements and a calming ambiance.

CREATIVITY AND MENTAL HEALTH: REDUCE STRESS, ANXIETY, AND DEPRESSION

Creativity has been shown to have a positive effect on mental health, specifically on reducing stress, anxiety, and depression. According to "Forbes" magazine, even just "coloring in those trendy coloring books" can improve your overall mental health. Making music, knitting, drawing, and any number of creative pursuits result in the production of dopamine, the hormone that makes us happy and a natural anti-depressant. Creating something also reduces your heart rate and helps lower anxiety. Even gardening can trigger this effect.

Creativity can also be useful in keeping your mind sharp and reducing your risk of dementia, as well as lessening the incidence of depression and loneliness.

CREATIVITY AND CHILDHOOD DEVELOPMENT

Creativity is great for adults, but children can also benefit from increasing their creativity. According to "PBS Ideastream," creativity "fosters mental growth in children by providing opportunities for trying out new ideas and new ways of thinking and problem-solving." They add that creative play allows children to express their feelings and celebrate their uniqueness. According to the National Association for the Education of Young Children (NAEYC), creative art processes also support a child's motor development (since they have to handle crayons, paint brushes, etc.) and "the development of self-regulation and self-control as the child focuses, makes choices and feels successful." According to the NAEYC, children learn best when there is no "set" project but rather when they are given materials and the freedom to make anything they want.

How To Unleash Your Creative Imagination

by philmckinney

Have you ever found yourself lost in your thoughts, daydreaming, or ideating without barriers? That's your creative imagination at work! Creative imagination is an incredible power within us—it can manifest our hopes, dreams, and aspirations. Unleashing the power of our creative imagination can be the key to realizing our personal and professional goals.

What is Creative Imagination?

Creative imagination is our ability to form mental images, concepts, and ideas that are unique and original. It is the source of our creativity, innovation, and imagination. Our creative imagination enables us to think outside the box and develop unconventional ideas, perspectives, and solutions.

It's a multidimensional process that involves both conscious and subconscious minds. It's a rich blend of our experiences, knowledge, intuition, and emotions. With creative imagination, we can visualize scenarios or solutions that don't yet exist, bridging the gap between the present and myriad possible futures.

Our creative imagination allows us to challenge conventions, break boundaries, and create new paradigms. It empowers us to perceive the world uniquely and interpret our experiences through fresh lenses. From creating a beautiful piece of art to pioneering a groundbreaking scientific theory, the power of creative imagination underlies all forms of human innovation and progress.

Each one of us possesses this power. However, like any other skill, it must be nurtured, cultivated, and practiced to reach its full potential.

How Does Creative Imagination Manifested?

"In a world of over 7 billion people, not a single person shares your unique creative imagination – that's your unmatchable superpower."

Creative imagination manifests in many ways, including daydreaming, visualization, ideation, and creativity. It is the source of our inspiration, motivation, and passion. Creative imagination is also associated with our ability to create and innovate and our capacity to explore and develop new ways of thinking. We use our creative imagination in our personal and professional endeavors, such as:

1) Problem-solving:

Whether figuring out a complex business challenge at work or deciding the best route to navigate a traffic jam, our creative imagination fuels our problem-solving abilities. It allows us to visualize multiple scenarios and outcomes, helping us to choose the most effective strategies.

2) Art and Creativity:

This is the most apparent manifestation of creative imagination, evident in the works of artists, writers, and musicians. These individuals draw upon their creative imagination to conceive and express unique ideas, emotions, and perspectives.

3) Innovation:

Every groundbreaking invention or discovery in history has been the product of someone's creative imagination. From Thomas Edison's light bulb to Elon Musk's vision for SpaceX, these innovations were once mere thoughts in the minds of their creators.

4) Learning and Education:

Students use creative imagination to understand and remember complex concepts. For instance, a student of history might imagine themselves in a historical event to understand its nuances better.

5) Personal Development:

Creative imagination can guide us in our personal growth and self-improvement efforts. By visualizing our ideal selves, we can map out the steps needed to reach our goals.

So, whether we are conscious of it or not, we constantly use our creative imagination to shape our world and experiences with its power.

The Power of Creative Imagination

Creative imagination has immense power! It can transform our lives by enabling us to serendipitously ideate, create, and innovate. Harnessing the power of our creative imagination can inspire us to achieve our goals and realize our ambitions. We can visualize our perfect lives, careers, and relationships and use our creative imagination to manifest these into reality. Here are some key aspects that highlight its significance:

1) Realizing Possibilities:

Creative imagination empowers us to visualize endless possibilities and solutions beyond our physical senses and immediate environment. It allows us to escape the constraints of the present moment, enabling us to travel in time and anticipate future outcomes. This ability to foresee potential scenarios aids in decision-making and strategizing, thus giving us an advantage in navigating life's challenges.

2) Driving Innovation:

The power of creative imagination is the cornerstone of all technological and societal advancements. It fuels the minds of scientists, inventors, and entrepreneurs, enabling them to create products, services, and solutions that reshape our world. Without creative imagination, there would be no iPhone, internet, or electric car.

3) Elevating Artistic Expression:

Creative imagination allows artists, writers, musicians, and performers to conceive and communicate unique ideas, emotions, and narratives in art and literature. It is the foundation of their creative process, transforming abstract thoughts and feelings into tangible works of art.

4) Personal Transformation:

On a personal level, creative imagination aids in self-improvement and personal development. Through visualization techniques, we can imagine our ideal selves, helping us to establish and pursue personal goals. By imagining our desired future, we can align our actions and behavior to those visions, leading to personal transformation and growth.

Increasing Your Creative Imagination

There are several actionable tips and steps to increase your creative imagination, including:

Foster curiosity

Curiosity, the innate desire to know and understand, is a fundamental driver of creative imagination. It prompts us to explore the unknown, question the familiar, and seek new experiences and perspectives. Fostering curiosity is an effective way to stimulate and harness your creative imagination. Here's how:

1. **Embrace the Unknown:** Step out of your comfort zone and delve into topics, cultures, or disciplines you know little about. This foray into the unfamiliar can trigger new ideas and insights, stimulating your creative imagination.
2. **Ask Questions:** Don't accept things at face value. Instead, ask “why,” “how,” and “what if” to delve deeper. This inquisitive mindset can lead to new connections and ideas.
3. **Seek Diverse Experiences:** Novel experiences broaden your perspectives, fueling your creative imagination. Travel to new places, read across various genres, engage with people from diverse backgrounds, or try out different cuisines.
4. **Lifelong Learning:** Commit to lifelong learning. Stay open to acquiring new skills, knowledge, and experiences. This continuous learning helps maintain a fresh and active mind ripe for creative imagination.

You keep your creative imagination vibrant, versatile, and ready by fostering curiosity. Remember, every great invention, every brilliant piece of art, and every revolutionary idea started with a curious mind.

Cultivating Creativity

Creativity forms the bedrock of the imaginative process, and fostering it can significantly enhance the power of your creative imagination. It translates your intangible thoughts into concrete expressions, cultivating your ability to conceive unique and innovative concepts. Here are some effective strategies to cultivate your creativity:

1. **Immerse in Diverse Art Forms:** Explore different artistic disciplines such as poetry, architecture, painting, or music. These arts incite fresh perspectives and can stimulate creative thinking. By appreciating the creativity of others, you can inspire your own.
2. **Free Writing or Drawing:** Set aside a specific time for free writing or drawing each day. This unstructured and spontaneous activity allows your thoughts to flow freely, releasing withheld creativity.
3. **Creative Spaces:** Designate a space for creative pursuits. This could be a room filled with art supplies, a corner with a musical instrument, or a quiet spot for writing. A dedicated creative space can help invoke your creative spirit.

4. **Collaboration:** Engage in group activities that require creative problem-solving. Collaboration exposes you to different ideas and perspectives, stimulating your creative imagination.

Creativity extends beyond art—it applies to every aspect of life. From solving complex problems to making everyday decisions, cultivating creativity can make you a more innovative thinker and help you harness your creative imagination to its fullest potential.

Engaging in Imagination

Engaging in imaginative activities is key to cultivating and strengthening your creative imagination. This practice allows you to flex your imagination, encouraging fresh perspectives and innovative ideas. Here's how you can engage in imagination:

1. **Visualization:** This is a powerful tool for mentally simulating a situation, concept, or object. By visualizing, you can explore possibilities, foresee challenges, and create solutions in your mind before taking any real-world actions. Athletes often use this technique to enhance their performance, and artists use it to conceive their creations.
2. **Daydreaming:** Contrary to popular belief, daydreaming isn't always a waste of time. It's a spontaneous, self-generated thought that allows your mind to wander freely. This can lead to the birth of original ideas and unique solutions you might not have discovered through analytical thinking alone.
3. **Reading Fiction:** Reading fiction is a form of ‘indirect' imaginative engagement. As you delve into different worlds, characters, and narratives, you indirectly stimulate your creative imagination, broadening your horizons and fostering empathetic and creative thinking.
4. **Playing ‘What If' Games:** Regularly challenging yourself with ‘what if' scenarios is a great way to stimulate your creative imagination. Pondering hypothetical situations forces you to think outside the box and develop creative solutions.

By regularly engaging in these imaginative exercises, you can effectively cultivate and enhance your creative imagination. Remember, your imagination is like a muscle – the more you use it, the stronger it gets.

Look With Fresh Eyes

Seeing the world with ‘fresh eyes‘ is a powerful way to harness your creative imagination. This involves perceiving things from a new perspective, challenging preconceived notions, and daring to think differently. Here are some ways to achieve this:

1. **Challenge Assumptions:** Question the status quo and challenge established assumptions. This may not only lead to innovative thoughts but can also stimulate out-of-the-box thinking.
2. **Reframe Problems:** View obstacles as opportunities and try to reframe problems into challenges. This shift in perspective can spark creative solutions.
3. **Practice Empathy:** Try to understand situations from other people's perspectives. This empathetic approach can broaden your worldview and stimulate diverse thought processes.
4. **Explore Multiple Angles:** Don't be content with the first solution or idea that comes to mind. Cultivate the habit of considering various facets of a problem or concept.

Keeping your eyes fresh and mind open, you can tap into the depths of your creative imagination, unlocking endless possibilities and fostering innovation. Remember, a fresh perspective is all you need to uncover the hidden gems waiting to be found in the world.

Keeping an Open Mind

Maintaining an open mind is a quintessential prerequisite for fostering your creative imagination. It allows you to explore new ideas, accept differing opinions, and step outside your comfort zone, which can fuel your creativity. Here are some ways to cultivate your creative imagination by keeping an open mind:

1. **Embrace Uncertainty:** Instead of fearing the unknown, embrace it. The uncertainty of new experiences can stimulate your imagination, pushing you to think in ways you haven't before.
2. **Welcome Different Perspectives:** Seek out and respect opinions that differ from your own. This can give you a broader range of ideas to draw from and enhance your creative thinking.
3. **Be Open to Learning:** Maintain a lifelong learner's attitude. This willingness to learn can expose you to many concepts and ideas, feeding your creative imagination.

4. **Experience Diversity:** Diversify your experiences and interactions. Engage with different cultures, philosophies, and lifestyles. The more varied your experiences, the richer your imagination becomes.
5. **Question Everything:** Adopt a questioning attitude. Explore the ‘ why ‘ behind things rather than taking information at face value.

Keeping an open mind facilitates a conducive environment for your creative imagination to flourish. It enables you to see beyond the obvious, question the ordinary, and venture into extraordinary possibilities. Remember, an open mind is the doorway to a world of creative potential.

Conclusion:

Your creative imagination is not just an intangible concept; it's a powerful force that can transform your personal and professional life. It can turn the ordinary into extraordinary, and the routine into remarkable. By nurturing your creative imagination through exercises, fresh perspectives, an open mind, and celebrating creativity, you're not just enhancing your problem-solving skills or improving your innovative thinking but unlocking a world of limitless possibilities. Thus enabling yourself to dream, explore, and create beyond the boundaries of common thought. You're equipping yourself with the ability to look at life through different lenses and to find opportunities where others see none.

But perhaps the most inspiring aspect of your creative imagination is its uniqueness. It's inherently yours – a reflection of your experiences, knowledge, and perspectives. No one else in the world possesses your creative imagination. Therefore, your creativity has the potential to contribute something truly unique and valuable to the world.

So, dare to imagine, create, and share your creativity with the world. Through your unique creative imagination, you can inspire others, make a difference, and leave a lasting impact.

Remember, every incredible creation today began as a mere figment of someone's imagination. So, who's to say what extraordinary creations your nurtured imagination might bring to life? Embrace your creative imagination, cherish it, and let it guide you through uncharted territories. The world awaits your creativity.

10 Best Industrial Design Companies in 2024

Christian Bourgeois . June 17, 2024

Transforming ideas into reality is no simple feat, especially when it comes to crafting innovative products that capture users' attention. That's where the best industrial design companies shine. These firms marry creativity, technical expertise, and a deep understanding of user needs to develop products that are as functional as they are beautiful.

From sleek consumer electronics to life-saving medical devices, the top industrial design companies have the skills and experience to bring even the most ambitious visions to life.

In this article, we'll introduce you to 10 of the most impressive industrial design firms making waves in 2024. Whether you're a startup looking to disrupt an industry or an established brand seeking to stay ahead of the curve, these companies have the talent and track record to help you achieve your goals.

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10 Top Industrial Design Companies

We've rounded up the best industrial design companies that can take your product from concept to consumer sensation. Whether you need to design a new gadget, update your product line, or create a unique user experience, these top industrial design studios have the skills and experience to make your product dreams a reality.

1. StudioRed

StudioRed

Best for

First-rate industrial design

Headquarters

Palo Alto, CA

Founded

1983

Notable clients
Meta, Microsoft, 7-Eleven, Medtronic

Industries: Consumer products, smart home products, Biomedical, Automation, Commercial and industrial

Target audience: Executives, product managers, directors of innovation, and other decision-makers in Fortune 500 companies

Production scale: Low-volume to million-unit production runs

StudioRed, a pioneering industrial design firm nestled in the heart of Silicon Valley, has been crafting innovative and economically viable solutions for over four decades. With an impressive portfolio spanning over 4,500 projects, StudioRed has established itself as the partner of choice for businesses seeking to transform bold ideas into market-defining products.

What sets StudioRed apart is its holistic approach to product development. The firm's multidisciplinary team of designers, engineers, and creators collaborates closely with clients, ensuring every aspect of the product lifecycle is carefully considered. From concept to manufacturing, StudioRed's expertise encompasses industrial design, ergonomics, user experience (UX) design, graphical user interface (GUI) design, mechanical engineering, and prototyping.

Unlike many other firms, StudioRed boasts in-house mechanical engineers and industrial designers. For most projects, they manage the entire process from concept through to manufacturing, resulting in tangible products. Many firms outsource their mechanical engineering, but StudioRed handles it internally.

StudioRed's highly collaborative culture between industrial designers and mechanical engineers allows them to streamline the development process, maintain better quality control, and efficiently bring innovative products to market.

Clients consistently praise StudioRed for its exceptional professionalism, structured approach, and ability to bring ideas to life. The firm's commitment to shepherding clients from blank slates to market leaders is validated by enduring partnerships with industry titans.

A deep empathy for stakeholder needs allows StudioRed to balance technical and creative demands while eliminating blind spots. This reliability has earned exceptional loyalty, with 90% of new clients returning and 95% of returning clients collaborating on three or more projects.

With a proven track record of successful product launches and over 200 international design awards, StudioRed continues to shape the future of product design. As a trusted advisor, the firm guides clients through the unknown challenges of product development, ensuring each project achieves enduring value and market success.

2. Whipsaw

Whipsaw

WHIPSAW

Best for
Innovative consumer product design
Headquarters
San Francisco, CA
Founded
1999
Notable clients
Uber, Tile, Google

Whipsaw is a renowned industrial design consultancy based in San Francisco. Whipsaw has spent over two decades creating award-winning product solutions across industries like consumer electronics, housewares, medical devices, robotics, and more. With a client roster featuring top brands like Google, Nike, Samsung, and Uber, Whipsaw's influence is evident in over 1,000 successful product launches.

The firm's design philosophy centers around crafting intuitive experiences that connect emotionally with end users. Whipsaw's creations exhibit a signature blend of beauty, functionality, and simplicity — qualities that have earned it over 300 major design accolades. Its human-centered approach, multidisciplinary talents, and commitment to design innovation have solidified Whipsaw as one of the world's preeminent industrial design practices.

3. Bould Design

Bould Design

Best for
Close collaboration
Headquarters
San Mateo, CA
Founded
2018
Notable clients
GoPro, Roku, Logitech

Bould Design is an industrial design studio that specializes in crafting innovative and successful products through user-centric design. The studio focuses on four key principles: function, simplicity, quality, and character, aiming to create products that are both functional and beautiful.

With a process that emphasizes collaboration and communication, Bould Design has worked with a wide range of clients, from startups to multinational corporations, and has consistently produced designs that earn high praise from users and critics alike. Its capabilities extend beyond industrial design to include branding and identity, packaging design, product visualization, and engineering support, ensuring Bould Design’s clients receive comprehensive solutions that bring their products to life.

4. Speck Design

Speck Design

speckdesign

Best for
Medical devices
Headquarters
San Jose, CA
Founded
1996
Notable clients
Cisco, Google, PopSockets

Speck Design, a Silicon Valley-based industrial design company, has been at the forefront of product design and strategy for nearly 30 years. The firm stands out for its ability to integrate innovation, aesthetics, and functionality, creating products that impact everyday life across homes, hospitals, and offices.

Speck Design’s diverse expertise allows it to tailor solutions throughout the innovation process, from ideation to manufacturing, particularly excelling in medical devices, consumer products, and wearables. Speck Design’s commitment to designing products that enhance human experiences reflects its dedication to a more inclusive and impactful future.

5. Frog

Frog

frog Part of
Capgemini Invent

Best for
Legacy and global influence
Headquarters
San Francisco, CA
Founded
1969
Notable clients
GE, Volvo Group, Purina

Frog is a global industrial design powerhouse crafting innovative products since 1969. Founded by Hartmut Esslinger in Germany, Frog pioneered an era of emotional design in response to the function-oriented products of the time. The company’s work caught the attention of Steve Jobs, leading to a partnership with Apple that produced iconic designs like the Apple IIc.

Over the decades, Frog has continued to evolve, integrating engineering, branding, and digital capabilities to help clients navigate technological disruptions and deliver exceptional customer experiences. Today, Frog collaborates with visionary leaders and entrepreneurs to build experiences and products that disrupt the status quo and realize the future.

6. NewDealDesign

NewDealDesign

new
deal
design

Best for
Emerging technologies
Headquarters
San Francisco, CA

Founded
2000
Notable clients
Fitbit, Herman Miller, Verizon

NewDealDesign is a San Francisco-based design studio founded in 2000 by Gadi Amit. The company is known for its innovative and human-centered approach to design, focusing on uniting technology and humanity in unconventional ways.

NewDealDesign consists of a team of industrial, graphic, and interaction designers and mechanical engineers who collaborate to develop cutting-edge technology products for clients such as Fitbit, Google, Intel, and more. The studio is recognized for its work in consumer electronics and wearable technology, and its designs have been praised for expanding appeal beyond niche markets to broader consumer audiences.

7. Box Clever

Box Clever

Best for
Consumer electronics and connected devices
Headquarters
San Francisco, CA
Founded
2012
Notable clients
Intuit, Arlo, Caraway

Box Clever is an industrial design company known for its various areas of expertise, including industrial, brand, packaging, and digital design. Fast Company has recognized Box Clever as one of the Top 10 Most Innovative Design Companies.

Box Clever is involved in a wide range of projects, including cookware, payment readers, and soap dispensers. They focus on creating innovative, high-quality products that challenge conventions. Box Clever approaches design by considering the full user journey, from use to cleaning and storage, and aims to create products that are functional, visually appealing, and modern.

8. Ammunition

Ammunition

ammunition

Best for
Lifestyle brands
Headquarters
San Francisco, CA
Founded
2007
Notable clients
Beats by Dre, Polaroid, Williams Sonoma

Ammunition is an industrial design and brand strategy consultancy recognized for its focus on user experience and its ability to integrate design, engineering, and brand strategy to create innovative products and experiences.

The company was influenced by Apple’s design approach and philosophy, where co-founder Robert Brunner previously worked.

This influence is reflected in Ammunition's attention to detail and commitment to creating visually appealing and high-quality products.

From Beats headphones to smart kitchen appliances, Ammunition's approach to design involves a deep understanding of the user and the market, as well as a focus on creating products that are both beautiful and functional. The company's work has garnered over 200 accolades, including the 2016 Cooper Hewitt National Design Award for Product Design.

9. Lifestyledesign

Lifestyledesign
lifestyledesign
Best for
Wearables
Headquarters
Santa Barbara, CA
Founded
2002
Notable clients
Patagonia, Under Armor, LG

Lifestyledesign is an industrial design consultancy that delivers solutions for brands in various industries, including lifestyle, consumer electronics, outdoor, sport, wearable technology, and IoT.

Lifestyledesign is known for its fashion-forward approach to design, aiming to connect with customers culturally and emotionally. With a focus on strategy, design, and development, Lifestyledesign offers a range of services, including brand strategy, product strategy, industrial design, UI/UX design, brand development, digital content creation, engineering, prototyping, and eyewear design.

10. Delve

Delve

Delve

Best for
Integrating strategy, creative, and technology
Headquarters
Madison, WI
Founded
1967
Notable clients
Black & Decker, Fiskars, First Alert

Delve is an industrial design agency with over 55 years of experience. It has a proven track record of delivering successful products, earning 1,500 patents and 200 design awards. Delve's approach involves human-centered strategy, design, and engineering to solve complex problems.

With expertise in various fields, including medical, industrial, automotive, and consumer products, Delve has delivered over 10,000 completed projects. The company is known for its multidisciplinary teams, which consist of product engineers, designers, and user researchers.

The Best Industrial Design Companies at a Glance

Company	Best for	Location	Years in Business
StudioRed	First-rate industrial design	Palo Alto, CA	41
Whipsaw	Innovative consumer product design	San Francisco, CA	25
Bould Design	A collaborative approach	San Mateo, CA	6
Speck Design	Medical devices	San Jose, CA	28

Company	Best for	Location	Years in Business
Frog	Legacy and global influence	San Francisco, CA	45
NewDealDesign	Emerging technologies	San Francisco, CA	24
Box Clever	Consumer electronics and connected devices	San Francisco, CA	12
Ammunition	Lifestyle brands	San Francisco, CA	17
Lifestyledesign	Wearables	Santa Barbara, CA	22
Delve	Integrating strategy, creative, and technology	Madison, WI	57

Why Work With an Industrial Design Company?

By tapping an industrial design company for product development, you gain access to a team of experienced professionals who can help you navigate this complex process. Some of the key benefits and services they provide include:

- **Market insight and trend analysis:** Industrial design companies keep their finger on the pulse of consumer preferences, industry trends, and emerging markets. They leverage this knowledge to inform the development of products that resonate with your target audience and stay ahead of the competition.
- **User-centric product development:** At the heart of every successful product is a deep understanding of the end user. Industrial designers excel at putting the customer first, conducting thorough research to uncover pain points and design solutions that truly meet their needs.
- **Brand strategy and consistency:** An industrial design firm helps ensure that any new product fits your brand identity and style guidelines. They recommend shapes, forms, materials, colors, and finishes that align with your brand vision.
- **Innovative and creative solutions:** Industrial designers are professionally trained to think outside the box. With their multidisciplinary expertise and access to the latest design tools and technologies, they are able to push boundaries and deliver breakthrough solutions that set your products apart.

- **Improved product usability and aesthetics:** Industrial designers strike the perfect balance between form and function, creating products that are both visually appealing and intuitive.
- **Access to specialized skills and technology:** Partnering with an industrial design firm gives you access to a cross-disciplinary team of specialists, integrating skills from engineering, human factors, and visual design. This allows you to tap into a wealth of knowledge and capabilities that may be difficult to replicate in-house.
- **Reduced time to market:** Industrial design companies have well-established processes and workflows that streamline the product development lifecycle, helping you get your innovations into customers' hands faster.
- **Maintaining design integrity and quality throughout product development:** An industrial design firm ensures that design intent is meticulously maintained throughout the entire product development process. With a focus on detail, with every aspect of the design carefully managed and monitored from concept through to production.

Services Industrial Design Companies Offer

Industrial design companies provide a wide range of services to assist with the entire product development lifecycle, from initial concept to final production. Although the specific offerings may vary between firms, the core services they usually provide include:

- **Market and user research:** Analyze trends, evaluate the competition, and determine what customers want to inform the product development process.
- **Concept development:** Generate and refine ideas for new products based on market research and client requirements.
- **Design for manufacturability (DFM):** Analyzing and selecting the appropriate colors, materials, and finishes to enhance the aesthetic appeal, functionality, and brand identity of a product.
- **Prototyping**: Build physical prototypes to test and validate product concepts, functionality, and usability.
- **Collaboration with engineering and manufacturing partners:** Work closely with engineering teams and manufacturing partners to ensure seamless integration of design concepts into final products.
- **Branding and packaging design:** Develop a cohesive visual identity and packaging designs that elevate the brand experience and attract customers.

Some industrial design companies may also offer more specialized services like DFM, UX, sourcing and supply chain management, and marketing and growth strategy. The key is finding a partner with the right capabilities and experience to match your specific product vision and goals.

How To Choose the Right Industrial Design Company

With so many industrial design firms to choose from, picking the right one to bring your product idea to life can feel overwhelming. But by focusing on a few key criteria, you can narrow the field and find a company that perfectly fits your needs. Here are five things to keep in mind during your search:

1. Define Your Budget and Project Requirements

Before shopping around for an industrial design firm, determine how much you can afford to invest in your product design. Do you have $10,000 to invest or $100,000? Are you seeking an industrial design company to conceptualize your startup idea or to facilitate the manufacturing process once the design is finalized? Be realistic about your budget and timeline.

Keep in mind that the total cost of your product development includes design, engineering, prototyping, testing, revisions, materials. Factor in expenses like tooling, manufacturing, and marketing to determine how much you can allocate to the product development.

It’s also important to have a clear understanding of your product goals, requirements, and constraints. Think through factors like:

- Product function and must-have features
- Target users and intended use cases
- Desired development timeline and milestones
- Required deliverables (concepts, CAD files, prototypes, etc.)
- Level of design support needed (research, branding concept development, design for manufacturing, and engineering support)

A well-defined design brief will make it easier to communicate your needs to potential partners and ensure you get relevant proposals to compare. Be as specific as possible about your requirements while staying open to the creative ideas and recommendations an experienced industrial design company can provide.

2. Evaluate Their Portfolio

A great way to gauge the design chops and range of an industrial design company is to review its past work. Study its portfolio to see what kinds of products it has designed in the past and whether its style matches what you're looking for.

Pay attention to details like material choices, ergonomics, and design intuitiveness. High-caliber design firms will have a proven track record of creating exceptional, impactful work. If products don't seem thoughtfully designed or you're left unimpressed, keep looking. Design is highly subjective, so go with your gut instinct here.

Look for companies that have experience designing a range of products similar to yours. Some firms specialize in certain industries or product types, while others are generalists. Either can be a great choice, depending on your needs.

3. Consider Industry Experience

While it's not necessarily a deal-breaker, working with an industrial design agency with experience in your particular industry can be a major advantage. With relevant experience comes valuable industry connections. Design firms develop close partnerships with contract manufacturers, component suppliers, and other players in the supply chain. Leveraging these connections can help get your product to market faster and more cost-efficiently.

Along the same lines, seek out firms that have designed for companies comparable to yours. Look at their client list and portfolio to find examples of work with companies of a similar size, market position, and business model as your own. Industrial design firms that typically partner with major multinationals may not provide the level of service and flexibility that smaller companies require.

4. Assess Their Process

The product development process can be long and complex, so it's important to understand how your potential design partner works and if their approach aligns with your needs and expectations. Ask them to walk you through their typical process from start to finish, including notable milestones, deliverables, and client touch points along the way.

Some important aspects to look for include:

- Thorough research and discovery phase to understand the market and user needs
- Iterative concept development with regular client feedback and collaboration
- Rapid prototyping and user testing to validate and refine the design direction
- Detailed design documentation and handoff to support manufacturing

- Proactive project management and communication to keep things on track

An experienced product design and development firm should have a mature and proven process in place but also be flexible enough to adapt to your unique needs and constraints. Avoid partners that are either too rigid in their ways or lack a clear methodology altogether.

5. Check Client Testimonials and References

When choosing a design firm, look for reviews from previous clients for insights into the company's work ethic and quality of service. Look for reviews that mention how quickly the company responded to questions and concerns. For a complex product design project, you'll want a partner that communicates well and addresses issues promptly.

Ask the companies you're interested in for client references and case studies of past projects. Reach out to the references they provide and ask specific questions about their experience, like:

- How did the overall experience working with the company go?
- Did they deliver concepts and designs on time and within budget?
- Were there any unexpected costs or delays?
- Were they receptive to feedback and willing to revise their designs?
- Did the final product meet your expectations and needs?

Speaking directly with references is the best way to judge an industrial design firm's capabilities and work style. Pay attention to both the content of the reviews and the enthusiasm in the client's voice. Lackluster or mediocre reviews and companies unwilling or unable to provide references are red flags.

FAQ

Have more questions about the ins and outs of industrial design companies? In this FAQ, we'll answer some common questions to help you understand what they do and how much it might cost to work with one.

What Is Industrial Design?

Industrial design is the professional practice of designing products, devices, objects, and services used by millions of people around the world every day. It is a multidisciplinary specialization aimed at creatively solving problems to improve products, systems, services, experiences, and businesses.

What Does an Industrial Designer Do?

Industrial designers consider the function, value, aesthetics, and usability of a product from the user's perspective. They blend art, science, and technology to create innovative solutions that benefit both the end user and the manufacturer. Key responsibilities of an industrial designer include conducting research, brainstorming ideas, prototyping, selecting materials, finalizing designs, and overseeing the manufacturing process.

How Much Does It Cost to Hire an Industrial Design Company for a Project?

The cost of hiring an industrial design company can vary significantly depending on several factors, including project scope and complexity, the design firm's expertise and reputation, project duration, and the specific services required.

Given these factors, the cost of an industrial design project can range from a few thousand dollars for a small, simple project to hundreds of thousands of dollars for a large, complex one.

It's important to note that many industrial design firms work on a project-based or hourly billing system, so the total cost can be challenging to estimate without a detailed project brief. The best approach is to consult with several reputable industrial design firms, provide them with your project requirements, and request detailed quotes for comparison.

The Value of an Experienced Industrial Design Firm

Choosing the right industrial design company is one of the most important decisions you'll make when developing a new product. A skilled and experienced firm can be the difference between a successful launch and a costly flop.

At StudioRed, we have a proven track record of guiding businesses through the entire product development process. Our multidisciplinary team works closely with clients to create innovative industrial design solutions that meet their unique needs.

If you’re seeking a reliable and reputable industrial design company to work with, contact us today. With our creativity, technical know-how, and commitment to user-centered design, StudioRed is the ideal partner for businesses looking to innovate and grow.

The Science of Creativity: How Your Brain Innovates

Creativity is the engine of human progress, driving groundbreaking innovations and transforming how we see the world. From the invention of the wheel to the development of artificial intelligence, creative thinking fuels every significant leap forward. But what exactly happens in your brain when inspiration strikes? Understanding the intricate science of creativity can reveal not only how ideas are born but also how you can nurture your innate ability to innovate.

The Neuroscience Behind Creativity

At its core, creativity is the result of complex neural interactions. Rather than originating from a single "creativity center," it involves multiple regions of the brain working together in harmony. Neuroscientists have identified key players like the prefrontal cortex, responsible for decision-making and problem-solving, and the hippocampus, which retrieves memories and generates new connections. These areas communicate via intricate neural pathways, allowing the brain to blend logic with imagination seamlessly.

Interestingly, studies show heightened activity in the brain's alpha waves during creative processes. These oscillations help suppress external distractions, enabling deeper focus and fostering a mental state conducive to generating novel ideas.

Left Brain vs. Right Brain: Debunking the Myth

For decades, popular culture has perpetuated the myth of the left brain being logical and the right brain being creative. While it's true that different hemispheres of the brain specialize in certain functions, creativity isn't confined to one side. Instead, it's the result of dynamic collaboration between both hemispheres.

For example, the left hemisphere excels at linguistic and analytical tasks, while the right hemisphere contributes spatial and emotional insight. Together, they create a balanced synergy, enabling nuanced thought processes and innovative breakthroughs. By debunking this outdated dichotomy, we can better appreciate the brain's holistic approach to creativity.

The Role of the Default Mode Network in Innovation

The default mode network (DMN), a network of interconnected brain regions, is a pivotal player in creativity. This network activates during rest, daydreaming, or introspection—moments when the mind wanders freely. The DMN facilitates divergent thinking, the process of exploring multiple possibilities and solutions.

Interestingly, some of the most creative ideas arise when people are least focused on the task at hand. Known as the "incubation effect," this phenomenon underscores the importance of downtime in fostering innovation. By allowing the DMN to operate unrestrained, the brain can form unexpected connections and unlock fresh perspectives.

Factors That Enhance Creative Thinking

Creativity isn't just an innate trait—it's a skill that can be cultivated. Various factors, both intrinsic and extrinsic, play a role in enhancing creative thinking:

1. **Curiosity**: A curious mind actively seeks new experiences and knowledge, which provide raw material for creative synthesis.
2. **Openness to Risk**: Taking calculated risks encourages unconventional thinking and the exploration of uncharted territories.
3. **Environment**: Stimulating environments filled with diverse stimuli can spark inspiration and fuel ingenuity.
4. **Mindfulness**: Practicing mindfulness increases self-awareness, allowing for deeper insights and sharper focus.

The Connection Between Emotions and Creativity

Emotions are a profound driver of creativity, shaping how we perceive and interpret the world. Positive emotions like joy and curiosity broaden cognitive flexibility, encouraging the exploration of new ideas. Conversely, emotions such as sadness can prompt introspection, leading to deeply meaningful and expressive creations.

Research highlights that emotional intensity, rather than the type of emotion, is often a key catalyst for creative breakthroughs. By embracing and channeling these feelings, individuals can unlock extraordinary creative potential.

Practical Ways to Boost Your Creative Potential

Nurturing creativity requires deliberate effort and practice. Here are actionable strategies to enhance your creative abilities:

1. **Engage in Cross-Disciplinary Learning**: Expose yourself to diverse fields to draw inspiration from unexpected sources.
2. **Practice Brainstorming**: Set aside time for unfiltered idea generation, allowing wild and unconventional concepts to emerge.
3. **Embrace Failure**: Treat mistakes as learning opportunities that pave the way for refinement and growth.
4. **Schedule Downtime**: Incorporate moments of relaxation into your routine to activate the default mode network.
5. **Experiment with Constraints**: Paradoxically, limiting resources or time can inspire innovative solutions by forcing you to think outside the box.

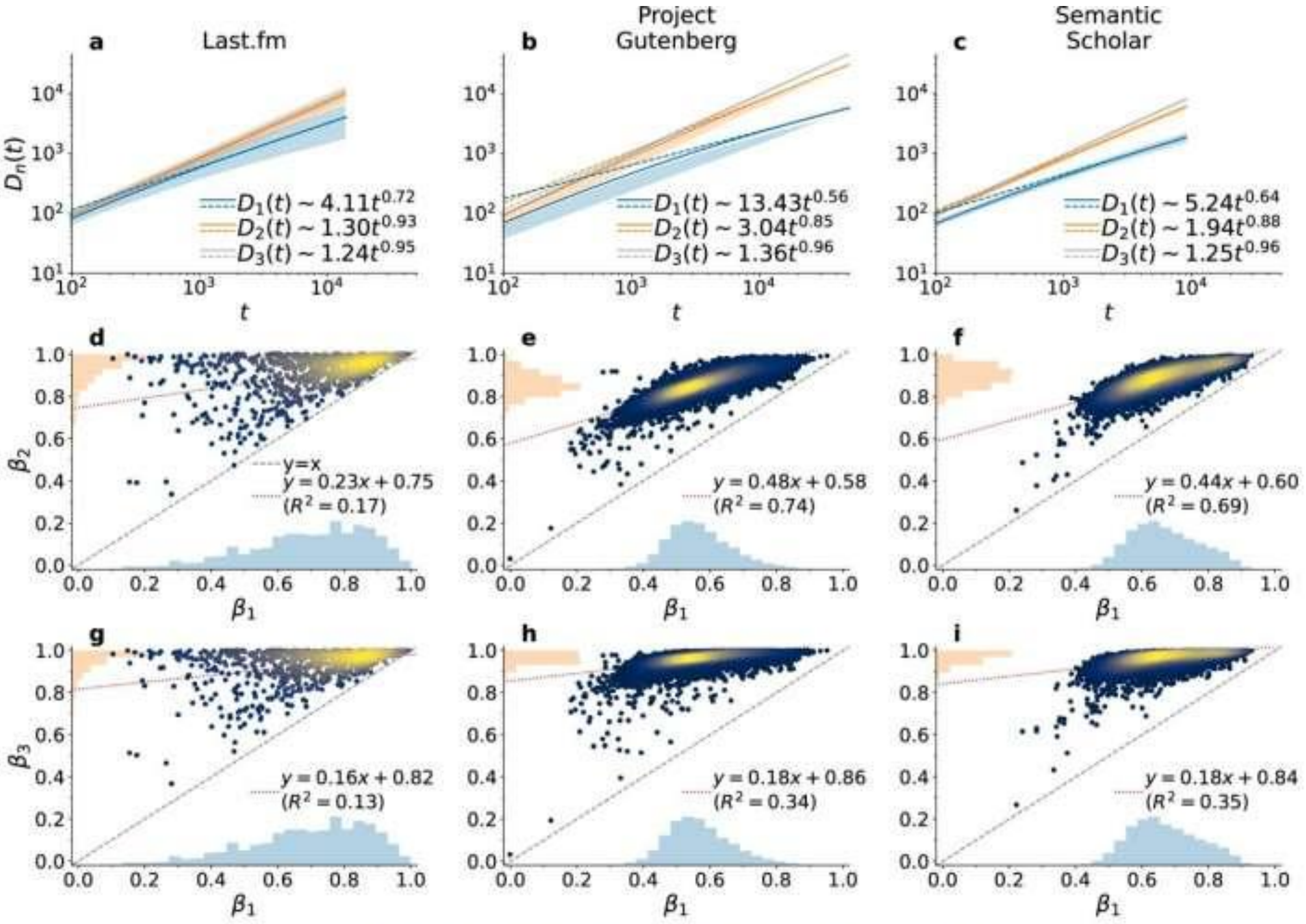
Summary

Creativity is a multifaceted phenomenon that reflects the brain’s boundless potential. By understanding the neuroscience behind it, we gain valuable insights into how ideas are formed and nurtured. Whether through engaging the default mode network, leveraging emotions, or adopting deliberate practices, anyone can enhance their capacity for innovation. Embrace your brain’s natural ingenuity, and let creativity guide you toward limitless possibilities.

JANUARY 29, 2025

Scientists map the mathematics behind how we create and innovate

by Tejasri Gururaj , Phys.org



Higher-order Heaps’ exponents in real-world data sets. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-024-55115-y

A new study in *Nature Communications* explores the dynamics of higher-order novelties, identifying fascinating patterns in how we combine existing elements to create novelty, potentially reshaping our understanding of human creativity and innovation.

Novelties—a common part of human life—refer to one of two things. The first is the discovery of a single item, like a place, song, or an artist. The second covers discoveries new to everyone, such as technological developments or drug discoveries.

The researchers in this study aimed to understand how both kinds of novelties emerge. The team was led by Prof. Vito Latora from the Queen Mary University of London, who spoke to Phys.org about the work.

"I have always been attracted by creativity and innovation, which are the driving forces of human progress. This paper is one of a sequence of theoretical and applied works of my research group to study and model the mechanisms underlying creativity, with the goal of understanding what makes a new idea, team, product, or technology successful," said Prof. Latora.

The team analyzed real-world data from three sources to study higher-order novelties.

First-time appearances

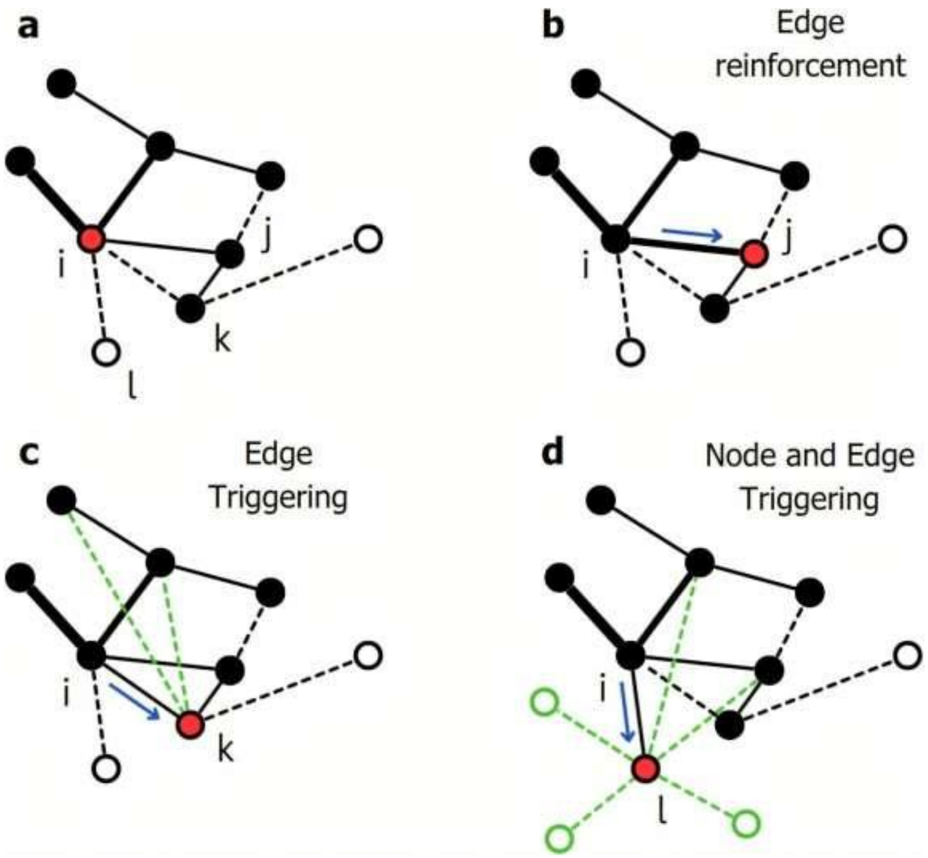
One of the main challenges with studying novelties is that most previous research has focused on first-order novelties, i.e., first-time appearances of individual elements.

For example, eating something new or visiting a new place for the first time. However, this approach overlooks an important innovation mechanism—combining existing elements to create something new.

For example, words can be strung together in different ways to create new poetry or stories, or musical notes can be combined to create a whole new song. The latter is known as higher-order novelties.

Prof. Latora said, "In our study, we introduced and explored a more general notion of novelty, which we named higher-order novelty, defined as the first time two or more elements appear together in a sequence."

To simulate how these combinations occur, the research team developed a framework called Edge-Reinforced Random Walk with Triggering or ERRWT.



The Edge-Reinforced Random Walk with Triggering (ERRWT) model. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-024-55115-y

Random walk and ERRWT

The ERRWT model is based on the random walk, a mathematical model that describes the evolution of a system based on discretized steps. In this method, the next position of the walker depends only on its current position.

The movement between positions is completely random, with each movement in each direction having equal probabilities.

Prof. Latora explained the process: "Imagine all the items we can explore, or all the ideas that we can have can be described as the nodes of a network, whose links represent relations or similarity between two items or concepts."

The model's innovation lies in how it simulates the evolution of these networks. As the walker moves through the network, it doesn't just traverse existing paths—it creates new connections, triggering the emergence of new nodes, mirroring how real-world discovery processes expand our horizon of possibilities.

The creation of new connections—when novel combinations occur—is known as edge triggering, and the strengthening of connections between frequently used combinations is known as edge reinforcement.

The team used this ERRWT model to analyze three datasets. They chose to analyze music listening patterns (Last.fm), literary texts and books (Project Gutenberg), and scientific articles (Semantic Scholar).

Prof. Latora explained how the model works, saying, "The more we listen to a song or we associate two songs, the higher is the probability that we will repeat the song or the association in the future. Moreover, this also implies that the discoveries of new songs or associations generate an expanding space of opportunities that are only available to us in the moment we unlock what is adjacent to them."

Heaps' law

The team discovered that the combinations followed predictable patterns, governed by Heaps' law, a power-law growth relationship. This is a mathematical relationship that describes how new combinations emerge over time, offering a quantitative way to measure and predict innovative processes.

According to their simulations, different processes can have the same rate of discovering individual elements but very different rates of discovering combinations.

More specifically, they found that for the Last.fm dataset, users with the same rate of discovering new songs can have very different paths in how they sequence these songs.

For the literature dataset, they found that writers tend to generate new word associations more often than introducing new words. Finally, scientific articles showed more creative word combinations compared to narrative texts, especially in paper titles.

The ERRWT showed how network structure and exploration patterns co-evolve, demonstrating that reinforcement (strengthening existing paths) and triggering (creating new connections) are necessary to explain real-world patterns.

Implications and future work

The new framework provides a new basis for understanding innovation and creativity, bridging the gap between individual discovery and combinatorial innovation.

The findings help us understand the relevance of this model, especially seeing how new scientific discoveries emerge from combinations of existing knowledge. It could also inform educational approaches to creativity.

Prof. Latora commented, "Studying creative processes and understanding how new ideas emerge and how novelties can trigger further discoveries is fundamental, if we want to devise effective interventions to nurture the success and sustainable growth of our society. We believe that our findings and proposed models can be directly used to answer questions about the rise and fall of popular items or ideas."

The research team aims to generalize the model further and also include a social component, which is presently missing.

More information: Gabriele Di Bona et al, The dynamics of higher-order novelties, *Nature Communications* (2025). DOI: 10.1038/s41467-024-55115-y.
Journal information: Nature Communications

How Creativity Positively Impacts Your Health

Creativity helps us perceive the world in new and different ways. It helps us create works of beauty, problem solve, and refresh our bodies and our minds. It's fun, and when you are having fun, you are positively impacting your health.

Creativity Improves Mental Health

Expressing yourself through artistic and creative activities is like a prescription for your mental health. Turning to creativity has been proven in extensive research to relieve both stress and anxiety. Creativity also helps lessen the shame, anger, and depression felt by those who have experienced trauma.[1]

The Walter Reed National Military Medical Center has an art therapy program for soldiers with PTSD. Veterans often find it difficult to express their trauma verbally. Art therapy manager Tammy Shella, PhD, ATR-BC, says, “Through art therapy, patients can convey how they really feel on the inside and reveal things that they weren’t comfortable sharing with the world.”[1]

Creativity Puts You in a Flow State

Have you ever been so immersed in writing in your journal, creating postcards out of your recent photographs, or dancing to your favorite band that you lost all sense of time?

Psychologist Mihaly Csikszentmihalyi, one of the cofounders of positive psychology, calls this “flow state.”[2] During this time, you’re focused with optimal attention on a task or activity. It’s sometimes called being *in the zone.*

This is an excellent and often euphoric state to be in. In this state, we are more mindful and relaxed. This allows us to feel more positive and brings a sense of accomplishment. People who experience flow report higher levels of creativity, productivity, and happiness.

How to Enhance Your Creativity

Maybe we don’t think of ourselves as artists or as innovators trained in coming up with bold, new ideas. However, the key traits of innovators include energy, intelligence and discipline, which we all have in varying amounts.

Although we might not be artists or innovators by profession, that doesn’t mean we can’t tap into ways to expand our creativity. We all have the ability to express ourselves and come up with alternate ways of looking at things.

The good news for those of us who didn’t excel at art during our childhood is that the beneficial effects happen during the art process. They are not based on the end product. Laurel Healy, LCSW, says, “Engaging in a creative process, like singing, dancing, painting or drawing, has full body benefits. When we focus on something that is challenging and/or fun, we make new neuropathways, increasing connectivity in the brain.

"Increased connectivity, especially in the left prefrontal cortex of the brain, makes us more emotionally resilient in a way that is similar to what occurs when we meditate. The release of dopamine brings an enhanced sense of well-being as well as improved motivation,” Healy says.

Draw or Paint

A growing body of research demonstrates that activities like drawing and painting can relieve stress and depression. Artistic activities have been linked to improving memory and resilience in older adults, even helping seniors with dementia reconnect with the world. Actively making art rather than simply appreciating art has also been shown to stave off cognitive decline.

octagonal electric teakettle Octagonal electric teakettle of hammered silver, with cane-wicker handle, designed by Peter Behrens for AEG (Allgemeine Elektricitäts Gesellschaft), Berlin, *c.* 1909.(more)

industrial design

Written by John Zukowsky

industrial design, the design of mass-produced consumer products. Industrial designers, often trained as architects or other visual arts professionals, are usually part of a larger creative team. Their primary responsibility is to help produce manufactured items that not only work well but please the eye and, therefore, have a competitive advantage over similar products. The work of an industrial designer often relates to or includes graphic design, such as advertising and packaging, corporate imagery and branding, and interior design (also called interior architecture or environmental design), the arrangement of man-made spaces.

Origins of modern design: Germany and Europe

Industrial design is a largely 20th-century phenomenon. The first industrial designer is often considered to be German architect Peter Behrens, who was heavily influenced by the 19th-century English designer and poet William Morris and by the Arts and Crafts movement, with which Morris was closely associated. Beginning in 1907, Behrens was the artistic adviser for AEG (the Allgemeine Elektricitäts Gesellschaft, or Universal Electric Company), for which he designed not only industrial buildings but also small electrical appliances, from teakettles to fans. In addition, he determined the company's corporate identity, packaging, and advertising. Behrens's approach was an extension of what architects such as Frank Lloyd Wright and Karl Friedrich Schinkel long practiced: total control of a designed environment at all levels. Behrens, however, created designs for a corporate client, intent on selling a service and related goods to the public, rather than for a middle-class residential client or a royal patron, as in the cases of Wright and Schinkel, respectively.

Behrens was a leading member of the Deutscher Werkbund (founded in 1907), a society of artists, architects, and craftsmen akin to English arts-and-crafts societies. The Deutscher Werkbund catalyzed communication among German design professionals and sponsored major exhibitions, such as those in Cologne (1914) and Stuttgart (1927); the latter was the Weissenhofsiedlung, a renowned exhibition of model homes designed by Europe's leading modern architects and the epitome of the International Style of minimalist architecture.

Barcelona chair and stool Barcelona chair and stool—designed in 1929 by Ludwig Mies van der Rohe—with cowhide straps and chromed steel frame, reproduced for Design Within Reach.(more)

Behrens himself influenced many architect-designers of the next generation, including Walter Gropius, founder of Germany's famed Bauhaus school of design, and Ludwig Mies van der Rohe, who served as a later director of the school. Founded in 1919 in Weimar, Ger., the Bauhaus aimed to elevate and coordinate the design and production of crafts and industrial goods for a new postimperial age. Both Gropius and Mies designed buildings as well as smaller-scale objects. For instance, Gropius was the architect of the new Bauhaus building when the school moved to Dessau in 1925, but he also designed interiors of Adler automobiles (1930–33). The furnishings designed at the Bauhaus were characterized by the extensive use of bent metal, something that was developed with the assistance of the Junkers Aircraft Company in Dessau, a firm known for its early development of the all-metal airplane in 1918, at the end of World War I. Mies—who directed the Bauhaus from 1930 to 1933, when the Nazi Party came to national power and closed it—designed some renowned examples of steel-framed furniture, such as the MR chair (1927), the Barcelona chair (1929), and the Brno chair (1930). During the worldwide Great Depression of the 1930s, when he had few architectural commissions, Mies earned a living from the royalties of those furniture sales. The Bauhaus produced other icons of modern design, notably the sleek glassware and streamlined table lamps of Wilhelm Wagenfeld.

Tecnolumen WA 24 table lamp Tecnolumen WA 24 table lamp, designed by Wilhelm Wagenfeld, nickel-plated metal with opaque glass globe, 1924.(more)

Beyond those designers specifically associated with the Bauhaus, other German architects of the time created high-profile designs; for instance, Fritz August Breuhaus de Groot created the interiors of the steamship *Bremen* (1929) and the airship *Hindenburg* (1931–35), and in the 1930s Gropius protégé Carl August Bembé designed motorboats for Maybach, a company that built internal-combustion engines for airplanes and boats and automobiles for the German car manufacturers Opel and Adler.

Savoy vase Savoy vase, designed in 1936 by Alvar Aalto, reproduced by Iittala, Inc.

Early developments in industrial design were not, however, taking place solely in Germany. In the first decades of the 20th century, architects and designers in other countries were also creating distinctively designed consumer products. These include such items as the undulating Savoy vase (1936) by the Finnish architect Alvar Aalto, the avant-garde geometric porcelain teapots and cups (1923) by Russian Suprematist painter Kazimir Malevich, the classic double-lever corkscrew (1930) by Italian designer Dominick Rosati, and the ubiquitous, highly flexible Anglepoise desk lamp (1932) by the British automotive engineer George Carwardine.

Modern design in the United States

Despite what is often seen as German leadership in creating industrial design as a profession, the United States has an equally compelling claim to being industrial design's parent country. The United States emerged from World War I (1914–18) physically undamaged; in contrast, many European cities and industrial facilities were not only damaged but in some cases downright decimated by those years of war and by the subsequent socialist and communist revolutions. In some ways the radical sociopolitical change of the interwar years catalyzed equally radical changes in attitudes toward design, as can be seen in the growing popularity of the Bauhaus within Weimar Germany. European society was in a state of turmoil and radical reform, but the United States, despite its share of social unrest, was somewhat more stable. During the war the country had established a reputation for large industrial production, and afterward its wartime factories were adapted for the civilian consumer economy. With this great output capability, most probably, came a tendency toward planned obsolescence. This term was supposedly coined after World War II by American industrial designers and writers to indicate industry's desire to produce consumer items that would be replaced even before their actual utility expired. Although the concept is often linked with the second half of the 20th century, it is likely that American industrialists saw this profit-making opportunity well before then.

The United States at this time was thus ripe for the development of the industrial design profession. In fact, the U.S. Patent Office recognized the term *industrial designer* in 1913, and, as in Europe, organizations were formed to unite the visual arts professionals who helped create consumer products and environments. The American Union of Decorative Artists and Craftsmen (founded in 1927), for instance, was followed by the American Designers Institute (1938) and the Society of Industrial Designers (1944), all of which eventually merged to form the Industrial Designers Society of America (1965). As with the Deutscher Werkbund and most professional organizations, these served to validate the profession in the view of the public and to facilitate communication among their members.

One of the first major public expressions of the newfound commitment to showcasing well-designed consumer products was Macy's department store's Art in Trade Exposition (1927), which was designed by the scenic designer and Theatre Guild founder Lee Simonson and owed a major conceptual debt to the Arts Décoratifs exposition that had taken place in Paris two years earlier. Throughout the rest of the interwar years, other exhibitions were likewise mounted to inform the public and endorse the objects and artists exhibited as well as to promote well-crafted consumer items. Even museums such as the new Museum of Modern Art (MoMA) in New York began to recognize the field; MoMA established a department of architecture and design (1932) and organized important exhibitions of industrial design, such as "Machine Art" (1934).

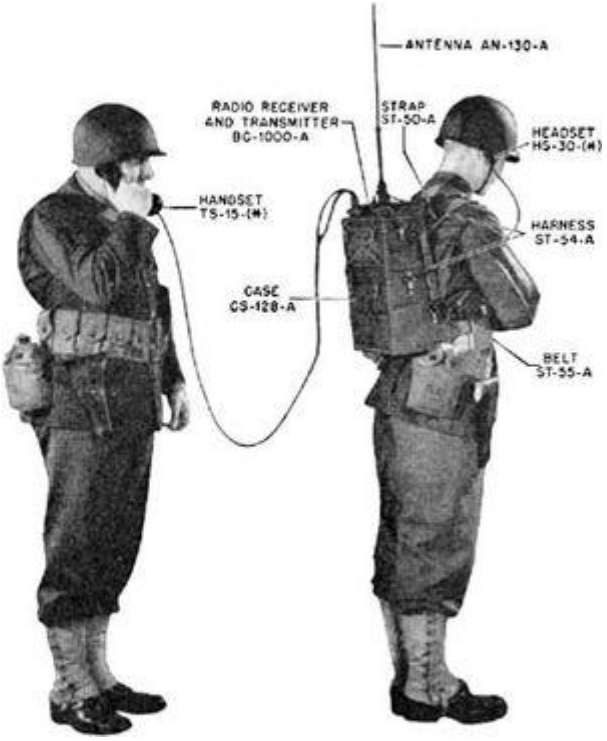
Moreover, department stores and direct-mail merchants, including Montgomery Ward and Sears, Roebuck and Company, created corporate design departments to control the look of their merchandise. Montgomery Ward was probably the first store in the United States to do so (1934), hiring design educator Ann Swainson to be their first woman executive and architect Dave Chapman to be the head of product planning. Sears followed soon afterward, scooping the competition by hiring noted German Modernist architect Karl Schneider, a Gropius and Behrens protégé, to design furniture and furnishings for the company's line (1938–45). In 1926 Walter Paepcke founded the Container Corporation of America, and in

1936 he hired Egbert Jacobson to establish a consistent design identity for its products and advertising, a development that had far-reaching consequences in the American graphic design and advertising worlds.

Loewy, Raymond: coffee shop at New York International Airport Coffee shop designed by Raymond Loewy, New York International Airport (now John F. Kennedy International Airport), Queens, New York, 1962.(more)

At this time several outstanding industrial designers were at work in the United States—among them Donald Deskey, Henry Dreyfuss, Walter Dorwin Teague, Raymond Loewy, and Norman Bel Geddes, who are often considered to be the founders of the industrial design profession in the United States. They created iconic items, ranging in scale from large (locomotive engines) to small (table lamps), that typify great moments in American design. These designers came from a variety of professional backgrounds, mostly in the visual arts. For instance, Donald Deskey was a furniture and interior designer who used an elaborate Art Deco style in his product design; his masterpiece was the interior of Radio City Music Hall in New York's Rockefeller Center (a contract he was awarded in 1932). Henry Dreyfuss is best known for his interest in ergonomics, particularly in his design of Bell telephones (1930 and later), but he is equally acclaimed for his bullet-shaped Hudson J3a locomotive (1938) for the New York Central Railroad, his interiors for Lockheed Aircraft and American Airlines, and his products for Thermos and Hoover. Engineer Raymond Loewy designed appliances for Sears, Roebuck and Company, but he is perhaps best remembered for his transportation design, from the S1 locomotive (1937) for the Pennsylvania Railroad and the Scenicruiser bus (1944 and later) for Greyhound to Studebaker automobiles (1953 and later). Packaging and advertising specialist Walter Dorwin Teague is best known for his design work on Kodak Brownie cameras (1927–30 and later) and on gas stations and corporate imagery for the Texas Fuel Company (1935–36; later renamed

Texaco), as well as his long-term work on Boeing airliner interiors, from the Stratocruiser (1945) through the 707 (1957–59). His firm, Walter Dorwin Teague Associates, continued to design Boeing airliner interiors into the 21st century. Joining those active and important practitioners was the more theoretically minded Norman Bel Geddes, a set designer best known for the futuristic transportation designs featured in his General Motors Pavilion and Futurama exhibit at the New York World's Fair (1939–40) and in his books *Horizons* (1932) and *Magic Motorways* (1940). The streamlined teardrop shape of his Motor Car No. 8 (1931) prefigured the similarly shaped Dymaxion car of American inventor R. Buckminster Fuller, unveiled at the 1933 Century of Progress Exposition in Chicago. Clean lines and streamlined shapes, suggestive of movement and speed, were characteristic of American design of the time and paralleled the design work produced by the aviation industry's wind-tunnel research of the 1920s and '30s.



Motorola Walkie-Talkie Motorola Walkie-Talkie, Model SCR-300-A, designed by Daniel E. Noble, Henry Magnuski, Bill Vogel, Lloyd Morris, and Marion Bond, 1941; illustration from the War Department Technical Manual TM11-242. The original walkie-talkie weighed about 35 pounds (16 kg) and had a range of about 2 miles (3 km).(more)

During World War II (1939–45) industrial designers came into their own, creating design solutions and products to help win the war, such as the Walkie-Talkie, a two-way FM radio invented by Galvin Manufacturing (later called Motorola, Inc.) in 1943 and used by the U.S. Army. These designers also helped to usher in a postwar consumer society after the long hiatus in individual spending that had begun with the Great Depression of the 1930s. Henry Dreyfuss, for example, worked for the Consolidated-Vultee Aircraft Company during the war; he proposed (1944) to convert the company's B-24 bombers into postwar airliners, and he planned and tested the Convair car (1947), a flying vehicle whose wings could be unbolted and whose fuselage could then function as an automobile, with that same company. Walter Dorwin Teague worked on converting the C97 military transport for Boeing into the double-decked Stratocruiser (1945) airliner, the conceptual forerunner of that company's jumbo jets. Buckminster Fuller reshaped his military Airbarac (1946), designed to serve as a metal barracks for the members of the army and air corps, into the all-aluminum Dymaxion House for the Beech Aircraft Company in Wichita, Kan. (today on exhibit at the Henry Ford Museum in Dearborn, Mich.). The war years catalyzed something else that had started during the Great Depression: architects' and designers' use of new and plentifully available materials, from aluminum and plastic to wood laminates. The postwar era witnessed a boom in industrial design throughout the world, as factories accustomed to churning out tens of thousands of machines for war transitioned to making mass-produced consumer goods. This was particularly so in the United States, where factories were not damaged or destroyed by wartime bombing. In a way, this circumstance guaranteed that American designers would be at the forefront of making consumer products immediately after the war.

American hegemony and challenges from abroad

Charles and Ray Eames: armchair Molded-plastic armchair reinforced with glass fibres, designed by Charles and Ray Eames, 1950.

American designers continued to be at the forefront of industrial design, at least in its initial postwar manifestation. Some major examples include advertising and packaging designer Walter Landor, who established Landor Associates (1941), a design consultancy renowned for creating brand identity and corporate imagery; industrial designer Charles Butler, a protégé of Raymond Loewy who in the 1950s and ’60s designed British airliner interiors, from Viscounts for Capital Airlines (1955) to the Concorde (1969 and later); Harley Earl, the creator of the design department at General Motors who was responsible for putting the fins on Cadillacs (1948 and later) and who also developed the Corvette sports car (1952–53); and Charles and Ray Eames, the husband-and-wife design team that popularized molded plywood furniture in the 1940s and ’50s. The design impact of the Eameses extended throughout American society, in part because they did not limit themselves to the design of furniture and furnishings. They created a number of important educational films, most notably *Powers of Ten* (1977), and they designed a number of significant public exhibitions, such as “Mathematica” (1961), that were shown throughout the nation and within World’s Fair pavilions. Other designers who made important contributions to American industry in the postwar era include Eliot Noyes, an employee of Norman Bel Geddes who in the 1950s and ’60s redesigned IBM’s product line, most notably the Selectric typewriter (1961); Richard Ten Eyck, who designed Cessna airplanes and Hesston tractors and is best known for designing the Vornado fan (1945–59, with 1988 and later variants) for the O.A. Sutton Corporation; and John Frassanito, a former Loewy employee who designed Datapoint computers in the early 1970s and spacecraft for NASA beginning in the mid-1980s.

Museums, both large and small, often showcased the work of such designers; the Albright Art Gallery in Buffalo, N.Y., for instance, organized the early exhibition “Good Design Is Your Business” in 1947, and MoMA displayed the best of design in its “Good Design” exhibitions (1950 and later). Also in those decades there was an expansion of the design curriculum within art and architectural schools. The Hungarian-born Bauhaus artist and educator László Moholy-Nagy established the trendsetting New Bauhaus in Chicago (1937) and subsequently developed the Institute of Design at Illinois Institute of Technology (1944). It and similar schools began to train the next generation of American industrial designers.

Industrial design flourished in postwar Europe as well. Even in war-ravaged West Germany, design was given a boost by the establishment of the Hochschule für Gestaltung in Ulm, or the Ulm Design School (1953–68), which was often considered a successor to the Bauhaus. One of its founders was the typeface designer Otl Aicher, a corporate-branding specialist, noted author of graphic standards manuals for his clients, and designer whose clients included Lufthansa and Munich’s transportation authority. Aicher’s contributions to the development of postwar graphic design and corporate identity may have even surpassed those of the legendary Herbert Bayer, the Bauhaus typeface designer who introduced a surrealistic collage style into periodicals of the 1930s and who continued his work in the United States with Gropius at Harvard after leaving Germany in 1938. After World War II, Bayer continued typeface innovations while helping design aficionado and industrialist Walter Paepcke to develop Aspen, Colo., as a resort and think tank location with the establishment of the Aspen Institute (1950). West Germany produced other great designers, such as Dieter Rams, who, beginning in 1955, was the creative force behind all Braun electric appliances, which epitomized the clean, minimalist look of modern German design.

Bang & Olufsen Beogram 4000 turntableA Bang & Olufsen Beogram 4000 turntable, designed by Jacob Jensen, 1972. It was the first turntable to use a tangential tonearm.(more)

After World War II, Japanese design benefited from an active reconnection to Europe and the United States. Japan's Ministry of International Trade and Industry (MITI), formed in 1949, sent Japanese industrial designers for study abroad in an effort to upgrade the quality of the country's products, which were considered, in the immediate postwar era, to be cheap imitations of Western products. Under this program Takuo Hirano—founder of one of Japan's largest industrial design firms, Hirano & Associates (1960)—studied at the Art Center College of Design in Pasadena, Calif. In 1957 MITI established the Good Design Awards (formerly the Good Design Selection System), or G-Marks. The G-Mark award system consists of an annual juried competition of new consumer products, with awards given for products within various categories and one grand prize that spans all. Awards are based on aesthetics of design as well as a product's features related to safety, function, value, and even post-sales consumer service. Such measures helped Japan become a worldwide leader in the export of home electronics and automobiles in the 1980s. Other countries also developed in terms of consumer product design after World War II. In Denmark, for instance, architect Arne Jacobsen established an international reputation with his iconic plywood-and-steel Ant chair (1951), and Jacob Jensen designed minimalist Bang & Olufsen stereo equipment from 1963 to 1993. In England the economical Mini automobile was created in 1959 by Morris Motors chief engineer Alec Issigonis and became an icon of the 1960s. The French architect Jean Prouvé created Modernist wood-and-metal furniture before and after the war. But perhaps the most remarkable postwar industrial design occurred in Italy.

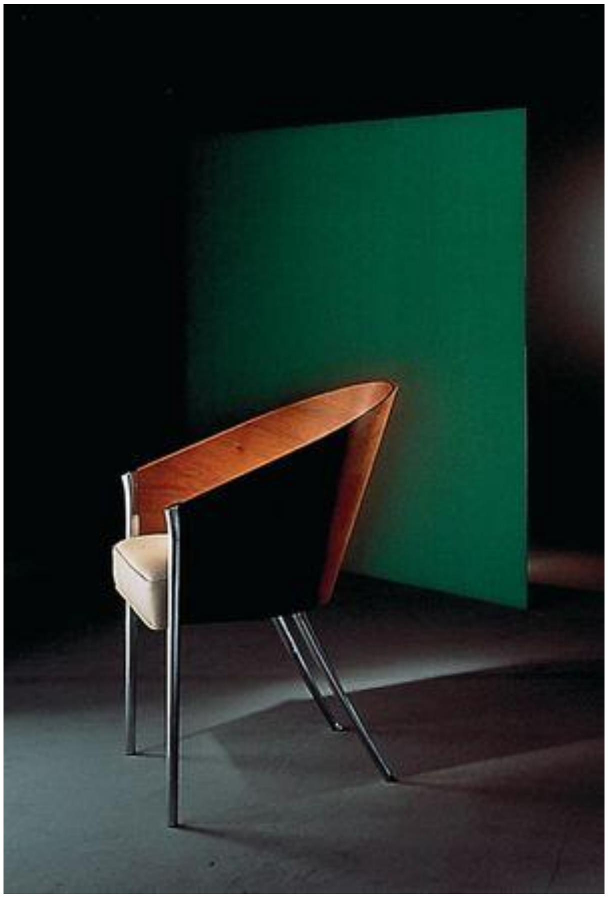
In the second half of the 20th century, Italian design was showcased for American museum audiences in exhibitions ranging from "Italy at Work" (1950) at the Art Institute of Chicago to "Italy: The New Domestic Landscape" (1972) at the MoMA in New York. In the former exhibition, Italian design captured the public's imagination with its sensual curvilinear forms; in the latter, museum visitors were shown the flexibility of modular furniture. Examples of great Italian product design created during the middle decades of the 20th century include Corradino d'Ascanio's peppy Vespa motor scooters (1946–48); Carlo Mollino's sensuous Arabesque table (1950); architect Vico Magistretti's lacquered aluminum Eclisse lamp (1965; also called the Eclipse lamp), which resembles a space helmet; artist Joe Colombo's innovative molded-plastic furniture, such as his 4867 Chair (1965) and popular Boby trolley (1970); Mario Bellini's calculators for the office-equipment company Olivetti beginning in the 1960s and continuing through the 1980s;

Alessandro Mendini's work in design publishing as well as kitchen-accessory design for the Italian design factory Alessi in the 1980s; and architect Ettore Sottsass's lifelong contributions to design for Olivetti (1958–80) and his founding in 1980 of the Memphis group of architects and designers. With its tendency to imbue its creations with whimsical historical references, this group was the epitome of postmodern design. Sottsass's work within the group includes his multicoloured Carlton room divider (1981).

Postmodern design and its aftermath

In the mid- to late 1970s, architects around the world began to question the validity of minimal Modernist architecture and design as providing the universal solution to all environments. There was a renewed appreciation of history and historic details and of local and regional historic contexts and a renewed expression of those historicist interests within popular exhibitions of the era, such as MoMA's renowned display in 1975–76 of 19th-century architectural renderings in watercolour from the École des Beaux-Arts and the First International Architecture Exhibition for the 1980 Venice Biennale, which took as its title and theme "The Presence of the Past." For this show, contemporary architects were encouraged to create streetscapes that related to traditional architectural environments.

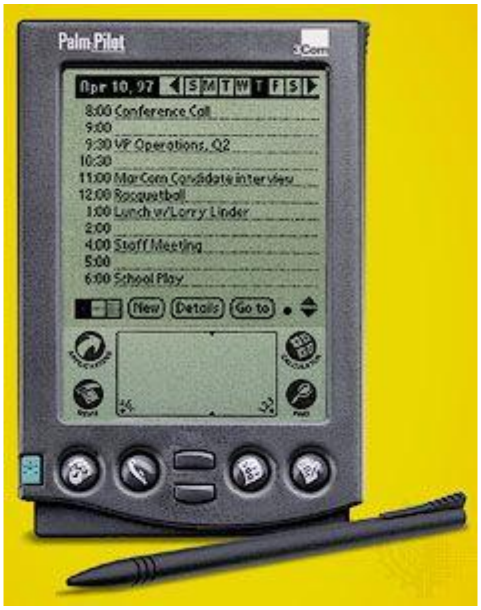
It was particularly in the postmodern 1980s that architects such as Michael Graves, Stanley Tigerman, and Hans Hollein created home accessories for companies such as Alessi in Milan and Swid Powell in the United States. Certain designers, including Sottsass and his Memphis colleague Matteo Thun of Austria, became household names, much as Mies and Breuer had been in the Modernist era, when their furniture designs were reissued by Knoll Associates and other companies. International exhibitions and publications, such as "Design Heute" (1988; "Design Today"), a traveling show organized by the German Architecture Museum in Frankfurt, displayed these often-outlandish postmodern creations for members of the public and professionals alike. This individualism reached its apex in the late 1980s, just before the recession of the early 1990s induced design to assume a more-subdued profile and pushed architecture into a more-sober focus on value engineering, an examination of the cost of the service and product provided in relation to its fulfillment of function.



Philippe Starck: Costes chair Costes chair, lacquered molded wood and leather by Philippe Starck, 1982.

Since then, two pronounced tendencies have been evident in industrial design: one showcases the artistic creations of a talented star designer, and the other relies on teamwork among design and engineering professionals to shape the final product. The former model is still evident in the field of architecture; witness the international celebrity achieved by Frank Gehry when he designed the Guggenheim Museum in Bilbao, Spain (1991–97). In product design and industrial design at the turn of the 21st century, however, few individuals achieved that sort of status. One exception is French designer Philippe Starck, whose plywood bucket chair called the Costes chair (1982) was popularized after he used it extensively in the Café Costes in Paris (1984). Starck continued to design dramatic interiors—most notably for hotels developed by entrepreneur Ian Schrager in the 1980s and '90s—as well as consumer products such as vases and toothbrushes. In a broadening of the public appeal for "designer" products, the department-store chain Target hired Michael Graves to develop a line of home furnishings, and, after that proved successful, Target enlisted Starck to do the same, with his products reaching stores in 2002. The wide public awareness of Starck's strong designs was an exception for industrial designers at the time.

The more-prevalent tendency in industrial design is for the designer to be part of a larger team that creates the marketable product. One important firm that embraced this approach was Frog Design. A company founded in 1969 by Hartmut Esslinger, it upheld the founder's idea that "form follows emotion," in contrast to the traditional Modernist dictum "form follows function." Frog Design is best known for its work on Sony Trinitron televisions (1978) and early Apple computers (1984). In the mid-1990s it expanded with offices in Europe and the United States to accommodate more clients, such as Lufthansa, for which it designed gate areas and airplane interiors, and Microsoft, which it advised on the design interface of the Windows XP operating system. Frog Design's Lufthansa work provides a good example of the firm's shift from expressing "function" to expressing corporate "emotion." The ribbed silver curvilinear design of Lufthansa's business-class seats relates to the tradition of the corrugated aluminum German airliners of the 1920s and '30s with their bucket seats. The check-in counters and waiting areas blend that early aviation vocabulary with medieval heraldic references, using curved forms to suggest a knight's shield protecting the check-in agents.



Palm Pilot Palm Pilot personal digital assistant (PDA).

Another teamwork-oriented design firm active at the start of the 21st century was IDEO. Founded in Palo Alto, Calif., in 1991 by Bill Moggridge, Mike Nuttall, and David Kelley, it grew rapidly, adding offices in San Francisco, Chicago, and Boston as well as London, Munich, and Shanghai. With its design studios operating globally, IDEO stressed the team approach to the design process. Its successfully executed projects are diverse and include the overall image and design of Amtrak's high-speed train Acela (2000), the original computer mouse for Microsoft (1987), modems for 3Com (2000), printers for Apple (1994) and Hewlett-Packard (1999), personal digital assistants for Palm, Inc. (1999), and for Palm’s competitor Handspring (2000), and even everyday items such as toothbrushes for Oral-B (1997) and CD-ROM cases for TDK (2000).

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aerospace industry: Design methods

In their global reach, both Frog Design and IDEO were typical of the design world at the turn of the millennium. Unlike their 20th-century counterparts (at least, perhaps, until the postmodern 1980s), such design firms practice internationally. This has contributed to the blurring of national identity in the look of designed products, with the exception of those few designers, like Starck, whose work is characterized by its individuality, though it is marketed throughout the world and on a very popular level through retail stores such as Target.

Mini Cooper SBMW's Mini Cooper S, 2002.

Further evidence of the globalization of industrial design can be seen in the automotive industry; many non-U.S. car companies maintain their design offices in California with staff members from around the world. One of the most-noted auto designers is J Mays, an American who trained at the Art Center College of Design in Pasadena, Calif., and then worked for German auto companies BMW and Audi in the 1980s. From 1989 to 1993 he served as chief designer of Volkswagen of America, where he devised the concept for the new Beetle (1998), the bulbous form of which recalled the basic lines of the original, designed by Ferdinand Porsche some 60 years earlier. In 1997 Mays was appointed head of Ford's design studio, which, under his direction, introduced the retro-looking Thunderbird (2002). International boundaries were likewise blurred when German carmaker BMW enlisted American designer Frank Stephenson to create the new Mini (2002), a revival of the iconic British car of the 1960s.

Design in the 21st century: technology and democracy

As in earlier decades, museums have continued to present industrial design to the public. Many museums specifically devoted to design were constructed, expanded, or remodeled during the 1980s and '90s; examples include the Design Museum and the Victoria and Albert Museum, both in London, the museums of applied art in Frankfurt and Vienna, the Musée des Arts Décoratifs in Paris, and the Neue Sammlung (New Collection) in Munich.

Even more spectacular new museums featuring industrial design products were established in the 21st century, the most notable being the Glass Pavilion of the Toledo Museum of Art in Ohio, U.S., designed by Kazuyo Sejima and Ryue Nishizawa (opened 2006); the Mercedes Benz Museum in Stuttgart, Ger., designed by Ben van Berkel of UN Studio (opened 2006); and the Harley-Davidson Museum in Milwaukee, Wis., U.S., designed in 2006 by Jim Biber of Pentagram Architecture.

While museum buildings and exhibits lent a seriousness to the field of industrial design, the general public was increasingly obtaining firsthand experience with affordable designed artifacts through successful chains of specialty stores that concentrated on home furnishings, such as Williams-Sonoma, Pottery Barn, Crate and Barrel, IKEA, and the EXPO Design Centers created by Home Depot. Those stores owed an enormous debt to the design mogul Sir Terence Conran and his pioneering designs for the Habitat Stores (1964 and later).

Conran wanted his stores to promote affordable, attractive, and functional modern goods to the general public. His consistently well-designed displays and products prefigured contemporary efforts by manufacturers such as Apple to effectively retail their products within a compatibly designed space. Tim Kobe of the San Francisco architectural firm Eight Inc. designed the standard Apple computer stores from the earliest establishments in San Francisco (2001) to shopping malls and renovated buildings across the United States (2001–04), including larger new structures in Chicago (2003) and New York (2006). In part because of the success of these spaces, Kobe's firm is planning and building similar standardized stores across the world for other firms. In all, these environments consistently present a company's products in a way that is both ennobling, as in a museum, and approachable. In one particular, specially designed stores are more effective tools than design museums because the consumer can actually touch and take home the products on display.

The public's increasing access to well-designed objects has been accompanied by a growing integration of technology into design. In part, this has been made possible by the wealth of new materials available to designers, from electronic liquid crystal displays to composites such as carbon fibre, which provides great strength despite its light weight. Since the 1980s, industrial designers have helped produce the small electronic appliances—including laptop computers, mobile telephones with video capabilities and GPS (Global Positioning System) devices, and iPods—that have permeated people's lives around the world.

John Zukowsky

green architecture

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green architecture, philosophy of architecture that advocates sustainable energy sources, the conservation of energy, the reuse and safety of building materials, and the siting of a building with consideration of its impact on the environment.

In the early 21st century the building of shelter (in all its forms) consumed more than half of the world's resources—translating into 16 percent of the Earth's freshwater resources, 30–40 percent of all energy supplies, and 50 percent by weight of all the raw materials withdrawn from Earth's surface. Architecture was also responsible for 40–50 percent of waste deposits in landfills and 20–30 percent of greenhouse gas emissions.

Many architects after the post-World War II building boom were content to erect emblematic civic and corporate icons that celebrated profligate consumption and omnivorous globalization. At the turn of the 21st century, however, a building's environmental integrity—as seen in the way it was designed and how it operated—became an important factor in how it was evaluated.

The rise of eco-awareness

In the United States, environmental advocacy, as an organized social force, gained its first serious momentum as part of the youth movement of the 1960s. In rebellion against the perceived evils of high-rise congestion and suburban sprawl, some of the earliest and most dedicated eco-activists moved to rural communes, where they lived in tentlike structures and geodesic domes. In a certain sense, this initial wave of green architecture was based on admiration of the early Native American lifestyle and its minimal impact on the land. At the same time, by isolating themselves from the greater community, these youthful environmentalists were ignoring one of ecology's most important principles: that interdependent elements work in harmony for the benefit of the whole.

Influential pioneers who supported a more integrative mission during the 1960s and early '70s included the American architectural critic and social philosopher Lewis Mumford, the Scottish-born American landscape architect Ian McHarg, and the British scientist James Lovelock. They led the way in defining green design, and they contributed significantly to the popularization of environmental principles. For example, in 1973 Mumford proposed a straightforward environmental philosophy:

Britannica Quiz

Architecture: The Built World

The solution of the energy crisis would seem simple: transform solar energy via plants and produce enough food power and manpower in forms that would eliminate the wastes and perversions of power demanded by our high-energy technology. In short, plant, eat, and work!

McHarg, who founded the department of landscape architecture at the University of Pennsylvania, laid the ground rules for green architecture in his seminal book *Design with Nature* (1969). Envisioning the role of human beings as stewards of the environment, he advocated an organizational strategy, called "cluster development," that would concentrate living centres and leave as much natural environment as possible to flourish on its own terms. In this regard McHarg was a visionary who perceived Earth as a self-contained and dangerously threatened entity.

This "whole Earth" concept also became the basis of Lovelock's Gaia hypothesis. Named after the Greek Earth goddess, his hypothesis defined the entire planet as a single unified organism, continuously maintaining itself for survival. He described this organism as

a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet.

During the 1970s the Norwegian environmental philosopher Arne Naess proposed a theory of "deep ecology" (or "ecosophy"), asserting that every living creature in nature is equally important to Earth's precisely balanced system. Working in exact opposition to this philosophy, the politics and economics of that decade accelerated the development of green awareness. The lack of business regulation in the United States meant unlimited consumption of fossil fuels. Meanwhile, the 1973 OPEC oil crisis brought the cost of energy into sharp focus and was a painful reminder of worldwide dependence on a very small number of petroleum-producing countries. This crisis, in turn, brought into relief the need for diversified sources of energy and spurred corporate and government investment in solar, wind, water, and geothermal sources of power.

Green design takes root

By the mid-1980s and continuing through the ’90s, the number of environmental advocacy societies radically expanded; groups such as Greenpeace, Environmental Action, the Sierra Club, Friends of the Earth, and the Nature Conservancy all experienced burgeoning memberships. For architects and builders a significant milestone was the formulation in 1994 of Leadership in Energy and Environmental Design (LEED) standards, established and administered by the U.S. Green Building Council. These standards provided measurable criteria for the design and construction of environmentally responsible buildings. The basic qualifications are as follows:

1. Sustainable site development involves, whenever possible, the reuse of existing buildings and the preservation of the surrounding environment. The incorporation of earth shelters, roof gardens, and extensive planting throughout and around buildings is encouraged.

2. Water is conserved by a variety of means including the cleaning and recycling of gray (previously used) water and the installation of building-by-building catchments for rainwater. Water usage and supplies are monitored.

3. Energy efficiency can be increased in a variety of ways, for example, by orienting buildings to take full advantage of seasonal changes in the sun’s position and by the use of diversified and regionally appropriate energy sources, which may—depending on geographic location—include solar, wind, geothermal, biomass, water, or natural gas.

4. The most desirable materials are those that are recycled or renewable and those that require the least energy to manufacture. They ideally are locally sourced and free from harmful chemicals. They are made of nonpolluting raw ingredients and are durable and recyclable.

5. Indoor environmental quality addresses the issues that influence how the individual feels in a space and involves such features as the sense of control over personal space, ventilation, temperature control, and the use of materials that do not emit toxic gases.

The 1980s and early ’90s brought a new surge of interest in the environmental movement and the rise to prominence of a group of more socially responsive and philosophically oriented green architects. The American architect Malcolm Wells opposed the legacy of architectural ostentation and aggressive assaults on the land in favour of the gentle impact of underground and earth-sheltered buildings—exemplified by his Brewster, Mass., house of 1980. The low impact, in both energy use and visual effect, of a structure that is surrounded by earth creates an almost invisible architecture and a green ideal. As Wells explained, this kind of underground building is “sunny, dry, and pleasant” and “offers huge fuel savings and a silent, green alternative to the asphalt society.”

The American physicist Amory Lovins and his wife, Hunter Lovins, founded the Rocky Mountain Institute in 1982 as a research centre for the study and promotion of the “whole system” approach favoured by McHarg and Lovelock. Years before the LEED standards were published, the institute, which was housed in a building that was both energy-efficient and aesthetically appealing, formulated the fundamental principle of authentic green architecture: to use the largest possible proportion of regional resources and materials. In contrast to the conventional, inefficient practice of drawing materials and energy from distant, centralized sources, the Lovins team followed the “soft energy path” for architecture—i.e., they drew from alternative energy sources.

The Center for Maximum Potential Building Systems (Max Pot; founded in 1975 in Austin, Texas, by the American architect Pliny Fisk III) in the late 1980s joined with others to support an experimental agricultural community called Blueprint Farm, in Laredo, Texas. Its broader mission—with applications to any geographic location—was to study the correlations between living conditions, botanical life, the growing of food, and the economic-ecological imperatives of construction. This facility was built as an integrative prototype, recognizing that nature thrives on diversity. Fisk concluded that single-enterprise and one-crop territories are environmentally dysfunctional—meaning, for example, that all of a crop’s predators converge, natural defenses are overwhelmed, and chemical spraying to eliminate insects and weeds becomes mandatory. In every respect, Blueprint Farm stood for diversified and unpredictable community development. The crops were varied, and the buildings were constructed of steel gathered from abandoned oil rigs and combined with such enhancements as earth berms, sod roofs, and straw bales. Photovoltaic panels, evaporative cooling, and wind power were incorporated in this utopian demonstration of the symbiotic relationships between farming and green community standards.

The American architect William McDonough rose to green design fame in 1985 with his Environmental Defense Fund Building in New York City. That structure was one of the first civic icons for energy conservation resulting from the architect’s close scrutiny of all of its interior products, construction technology, and air-handling systems. Since then, McDonough’s firm established valuable planning strategies and built numerous other green buildings—most significantly, the Herman Miller factory and offices (Holland, Mich., 1995), the corporate offices of Gap, Inc. (San Bruno, Calif., 1997), and Oberlin College's Adam Joseph Lewis Center for Environmental Studies (Oberlin, Ohio, 2001).

McDonough's main contribution to the evolution of sustainable design was his commitment to what he has called "ecologically intelligent design," a process that involves the cooperation of the architect, corporate leaders, and scientists. This design principle takes into account the "biography" of every aspect of manufacture, use, and disposal: the choice of raw ingredients, transport of materials to the factory, fabrication process, durability of goods produced, usability of products, and recycling potential. McDonough's latest version of the principle—referred to as "cradle-to-cradle" design—is modeled after nature's own waste-free economy and makes a strong case for the goal of reprocessing, in which every element that is used in or that results from the manufacturing process has its own built-in recycling value.

Principles of building green

The advances in research and in building techniques achieved by the above-mentioned green design luminaries have been compiled into a reliable database of environmental construction methods and sustainable materials—some of which have been in use for thousands of years yet remain the basis for contemporary advances in environmental technology. For private residences of the 21st century, the essential green design principles are as follows:

- *Alternative energy sources*. Whenever feasible, build homes and communities that supply their own power; such buildings may operate entirely off the regional power grid, or they may be able to feed excess energy back onto the grid. Wind and solar power are the usual alternatives. The quality of solar collectors and photovoltaic panels continues to improve with the advance of technology; practical considerations for choosing one supplier over another include price, durability, availability, delivery method, technology, and warranty support.

- *Energy conservation*. Weatherize buildings for maximum protection against the loss of warm or cool air. Major chemical companies have developed responsibly manufactured, dependable, moisture-resistant insulating materials that do not cause indoor humidity problems. Laminated glass was also radically improved at the end of the 20th century; some windows provide the same insulation value as traditional stone, masonry, and wood construction. In regions that experience extreme heat, straw-bale or mud-brick construction—used since ancient times—is a good way to save money and energy.

- *Reuse of materials*. Use recycled building materials. Although such products were scarce in the early 1990s, since the early 21st century they have been readily available from a burgeoning number of companies that specialize in salvaging materials from demolition sites.
- *Careful siting*. Consider using underground or earth-sheltered architecture, which can be ideal for domestic living. Starting at a depth of about 1.5 metres (5 feet) below the surface, the temperature is a constant 52 °F (11 °C)—which makes the earth itself a dependable source of climate control.

Lillis Business Complex; University of Oregon The Lillis Business Complex, known for its environmentally friendly design, for having one of the largest solar installations in the Northwest, and for its innovative use of photovoltaic solar glass, on the campus of the University of Oregon in Eugene, Oregon.(more)

Individual, corporate, and governmental efforts to comply with or enforce LEED standards include recycling at household and community levels, constructing smaller and more efficient buildings, and encouraging off-the-grid energy supplies. Such efforts alone cannot preserve the global ecosystem, however. On the most basic level, the ultimate success of any globally sanctioned environmental movement depends as much on its social, psychological, and aesthetic appeal as on its use of advanced technologies.

The environmental movement in the 21st century can succeed only to the extent that its proponents achieve a broad-based philosophical accord and provide the same kind of persuasive catalyst for change that the Industrial Revolution offered in the 19th century. This means shaping a truly global (as well as optimistic and persuasive) philosophy of the environment. Much depends on the building arts and integrative thinking. Architects will have to abandon 20th-century specialization and reliance on technology and, with builders and clients, help support grassroots, community-oriented, and globally unifying objectives. In the words of Earth Day founder Gaylord Nelson,

The ultimate test of man's conscience may be his willingness to sacrifice something today for future generations whose words of thanks will not be heard.

Challenges to architecture

If architecture is to become truly green, then a revolution of form and content—including radical changes in the entire look of architecture—is essential. This can only happen if those involved in the building arts create a fundamentally new language that is more contextually integrative, socially responsive, functionally ethical, and visually germane.

The potentialities of environmental science and technology must be creatively examined. Already there exists a rich reservoir of ideas from science and nature—cybernetics, virtual reality, biochemistry, hydrology, geology, and cosmology, to mention a few. Furthermore, just as the Industrial Revolution once generated change in many fields in the 19th century, so too the information revolution, with its model of integrated systems, serves as a conceptual model in the 21st century for a new approach to architecture and design in the broader environment.

Understand the importance of incorporating sustainable design thinking and practice in buildings and city spaces Learn about the use of plants in green architecture.(more)
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As community governments begin to legislate state-of-the-art green standards, they must encourage appropriate artistic responses to such regional attributes as surrounding topography, indigenous vegetation, cultural history, and territorial idiosyncrasy. For instance, communities might encourage innovative fusions of architecture with landscape—where trees and plants become as much a part of architectural design as construction materials—so that buildings and their adjacent landscapes essentially merge. In such thinking, buildings are not interpreted as isolated objects, and the traditional barriers between inside and outside and between structure and site are challenged.

Likewise, green architecture in the 21st century has similar obligations to the psychological and physical needs of its inhabitants. Buildings are most successful when they respond to multiple senses—meaning that truly green design engages touch, smell, and hearing as well as sight in the design of buildings and public spaces.

Continuing advances in environmental technology have significantly strengthened the goals of sustainable architecture and city planning over the last decade. Yet many people consider the environmental crisis beyond their comprehension and control. Though technological solutions are necessary, they represent only one facet of the whole. Indeed, the transfer of responsibility to engineers and scientists threatens the social and psychological commitment needed for philosophical unity.

Increasing numbers of people seek new symbiotic relationships between their shelter and the broader ecology. This growing motivation is one of the most promising signs in the development of a consensus philosophy of the environment. As the environmental movement gains momentum, it underlines the anthropologist Margaret Mead's observation:

Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it is the only thing that ever has.

James Wines

materials science

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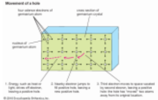

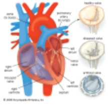

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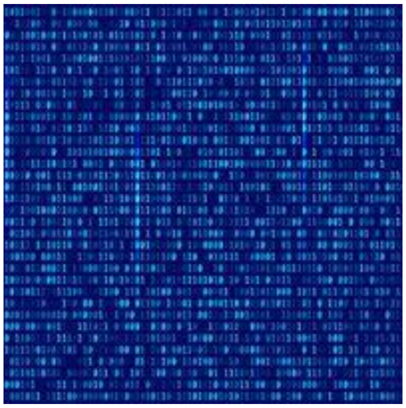

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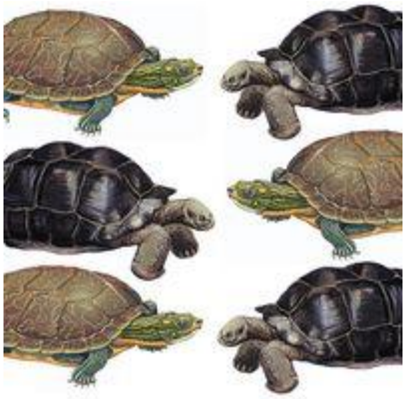

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materials science, the study of the properties of solid materials and how those properties are determined by a material's composition and structure. It grew out of an amalgam of solid-state physics, metallurgy, and chemistry, since the rich variety of materials properties cannot be understood within the context of any single classical discipline. With a basic understanding of the origins of properties, materials can be selected or designed for an enormous variety of applications, ranging from structural steels to computer microchips. Materials science is therefore important to engineering activities such as electronics, aerospace, telecommunications, information processing, nuclear power, and energy conversion.

This article approaches the subject of materials science through five major fields of application: energy, ground transportation, aerospace, computers and communications, and medicine. The discussions focus on the fundamental requirements of each field of application and on the abilities of various materials to meet those requirements.

The many materials studied and applied in materials science are usually divided into four categories: metals, polymers, semiconductors, and ceramics. The sources, processing, and fabrication of these materials are explained at length in several articles: metallurgy; elastomer (natural and synthetic rubber); plastic; man-made fibre; and industrial glass and ceramics. Atomic and molecular structures are discussed in chemical elements and matter. The applications covered in this article are given broad coverage in energy conversion, transportation, electronics, and medicine.

Materials for energy

An industrially advanced society uses energy and materials in large amounts. Transportation, heating and cooling, industrial processes, communications—in fact, all the physical characteristics of modern life—depend on the flow and transformation of energy and materials through the techno-economic system. These two flows are inseparably intertwined and form the lifeblood of industrial society. The relationship of materials science to energy usage is pervasive and complex. At every stage of energy production, distribution, conversion, and utilization, materials play an essential role, and often special materials properties are needed. Remarkable growth in the understanding of the properties and structures of materials enables new materials, as well as improvements of old ones, to be developed on a scientific basis, thereby contributing to greater efficiency and lower costs.

Classification of energy-related materials

Energy materials can be classified in a variety of ways. For example, they can be divided into materials that are passive or active. Those in the passive group do not take part in the actual energy-conversion process but act as containers, tools, or structures such as reactor vessels, pipelines, turbine blades, or oil drills. Active materials are those that take part directly in energy conversion—such as solar cells, batteries, catalysts, and superconducting magnets.

Another way of classifying energy materials is by their use in conventional, advanced, and possible future energy systems. In conventional energy systems such as fossil fuels, hydroelectric generation, and nuclear reactors, the materials problems are well understood and are usually associated with structural mechanical properties or long-standing chemical effects such as corrosion. Advanced energy systems are in the development stage and are in actual use in limited markets. These include oil from shale and tar sands, coal gasification and liquefaction, photovoltaics, geothermal energy, and wind power. Possible future energy systems are not yet commercially deployed to any significant extent and require much more research before they can be used. These include hydrogen fuel and fast-breeder reactors, biomass conversion, and superconducting magnets for storing electricity.

Classifying energy materials as passive or active or in relation to conventional, advanced, or future energy systems is useful because it provides a picture of the nature and degree of urgency of the associated materials requirements. But the most illuminating framework for understanding the relation of energy to materials is in the materials properties that are essential for various energy applications. Because of its breadth and variety, such a framework is best shown by examples. In oil refining, for example, reaction vessels must have certain mechanical and thermal properties, but catalysis is the critical process.

Applications of energy-related materials

High-temperature materials

In order to extract useful work from a fuel, it must first be burned so as to bring some fluid (usually steam) to high temperatures. Thermodynamics indicates that the higher the temperature, the greater the efficiency of the conversion of heat to work; therefore, the development of materials for combustion chambers, pistons, valves, rotors, and turbine blades that can function at ever-higher temperatures is of critical importance. The first steam engines had an efficiency of less than 1 percent, while modern steam turbines achieve efficiencies of 35 percent or more. Part of this improvement has come from improved design and metalworking accuracy, but a large portion is the result of using improved high-temperature materials. The early engines were made of cast iron and then ordinary steels. Later, high-temperature alloys containing nickel, molybdenum, chromium, and silicon were developed that did not melt or fail at temperatures above 540° C (1,000° F). But modern combustion processes are nearing the useful temperature limits that can be achieved with metals, and so new materials that can function at higher temperatures—particularly intermetallic compounds and ceramics—are being developed.

The structural features that limit the use of metals at high temperatures are both atomic and electronic. All materials contain dislocations. The simplest of these are the result of planes of atoms that do not extend all through the crystal, so that there is a line where the plane ends that has fewer atoms than normal. In metals, the outer electrons are free to move. This gives a delocalized cohesion so that, when a stress is applied, dislocations can move to relieve the stress. The result is that metals are ductile: not only can they be easily worked into desired shapes, but when stressed they will gradually yield plastically rather than breaking immediately. This is a desirable feature, but the higher the temperature, the greater the plastic flow under stress—and, if the temperature is too high, the material will become useless. In order to get around this, materials are being studied in which the motion of dislocations is inhibited. Ceramics such as silicon nitride or silicon carbide and intermetallics such as nickel aluminide hold promise because the electrons that hold them together are highly localized in the form of valence or ionic bonds. It is as if metals were held together by a slippery glue while in nonmetals the atoms were connected by rigid rods. Dislocations thus find it much harder to move in nonmetals; raising the temperature does not increase dislocation motion, and the stress needed to make them yield is much higher. Furthermore, their melting points are significantly higher than those of metals, and they are much more resistant to chemical attack. But these desirable features come at a price. The very structure that makes them attractive also makes them brittle; that is, they do not flow when subject to a high stress and are prone to failure by cracking. Modern research is aimed at overcoming this lack of ductility by modification of the material and how it is made. Hot pressing of ceramic powders, for example, minimizes the number of defects at which cracks can start, and the addition of small amounts of certain metals to intermetallics strengthens the cohesion among crystal grains at which fractures normally develop. Such advances, along with intelligent design, hold the promise of being able to build heat engines of much higher efficiency than those now available.

Diamond drills

Diamond drill bits are an excellent example of how an old material can be improved. Diamond is the hardest known substance and would make an excellent drill bit except that it is expensive and has weak planes in its crystal structure. Because natural diamonds are single crystals, the planes extend throughout the material, and they cleave easily. Such cleavage planes allow a diamond cutter to produce beautiful gems, but they are a disaster for drilling through rock. This limitation was overcome by Stratapax, a sintered diamond material developed by the General Electric Company of the United States. This consists of synthetic diamond powder that is formed into a thin plate and bonded to tungsten-carbide studs by sintering (fusing by heating the material below the melting point). Because the diamond plate is polycrystalline, cleavage cannot propagate through the material. The result is a very hard bit that does not fail by cleavage when it is used to drill through rock to get at oil and natural gas.

Oil platforms

An important example of dealing with old problems by modern methods is provided by the prevention of crack growth in offshore oil-drilling platforms. The primary structure consists of welded steel tubing that is subject to continually varying stress from ocean waves. Since the cost of building and deploying a platform can amount to several billion dollars, it is imperative that the platform have a long life and not be lost because of premature metal failure.

In the North Sea, 75 percent of the waves are higher than two metres (six feet) and exert considerable stresses on the platform. Cyclic loading of a metal ultimately results in fatigue failure in which surface cracks form, grow over time, and eventually cause the metal to break. Welds are the weak spots for such a process because weld metal has mechanical properties that are inferior to steel, and these are made even worse by internal stresses and defects (such as tiny voids and oxide particles) that are introduced in the welding process. Furthermore, the tube geometry at the weld consists of T- and K-shaped joints, which are natural stress concentrators. Fatigue failure in oil platforms therefore takes place at welds.

Fatigue occurs because cyclic stress causes dislocations to form and to move back and forth in the metal. Dislocation motion can be impeded by the presence of barriers such as small voids, grain boundaries, other dislocations, impurities, or even the surface itself. When dislocations are thereby pinned down, they stop the motion of other dislocations created by the stress, and a tangled dislocation network forms that results in a hard spot in the weld. The stress is then not easily relieved, and types of dislocation motion that are characteristic of the fatigue process initiate a crack at the weld surface. This phenomenon is a direct result of the microstructure of the weld and could be minimized by making the weld very uniform, preferably of the same material as the tubing, and having a very gently curved geometry at the joint. But, in spite of the sophistication of modern welding techniques, this is not yet feasible. An alternate strategy is therefore used in which the progress of the weld crack is monitored so that repairs can be made in time to avoid catastrophic failure. This can be done because, given the geometry of the joint, the depth of the crack is proportional to time until the crack is quite large. By contrast, in laboratory tests in which simple strips of metal are subject to cyclic stress, the growth rate increases as the crack becomes larger. In the T or K configuration in oil platforms, stress is much more evenly distributed, and the crack does not grow at an increasing speed until it is close to being fatal.

A technique for measuring the crack depth is based on the skin effect, the phenomenon in which a high-frequency alternating current is confined to the surface of a conductor. This makes it possible to measure the surface area of a small region with a simple meter, since an increase in crack depth means an increase in current path, and this in turn causes an increase in voltage drop. Measurement over time then allows the time to failure to be estimated; repairs can be effected before failure occurs. In this case, a knowledge of microstructure, the materials science of fatigue, and the study of crack formation have led to a simple testing technique of great economic importance.

Mathematical modeling of mass motion and heat transfer (including convection), along with studies of solidification, gas dissolution, and the effects of fluxes, are providing a much more detailed understanding of the factors controlling weld structure. With this knowledge, it should be possible to make welds with far fewer defects.

Radioactive waste

A different example is provided by the disposal of radioactive waste. Here the issue is primarily safety and the perception of safety rather than economics. Waste disposal will continue to be one of the factors that inhibit the exploitation of nuclear power until the public perceives it as posing no danger. The current plan is to interpose three barriers between the waste and human beings by first encapsulating it in a solid material, putting that in a metal container, and finally burying that container in geologically stable formations. The first step requires an inert, stable material that will hold the radioactive atoms trapped for a very long time, while the second step requires a material that is highly resistant to corrosion and degradation.

There are two good candidates for encapsulation. The first is borosilicate glass; this can be melted with the radioactive material, which then becomes a part of the glass structure. Glass has a very low solubility, and atoms in it have a very low rate of migration, so that it provides an excellent barrier to the escape of radioactivity. However, glass devitrifies at the high temperatures resulting from the heat of radioactive decay; that is to say, the amorphous glassy state becomes crystalline, and, during this process, many cracks form in the material so that it no longer provides a good barrier against the escape of radioactive atoms. (This problem is more severe in rock than in salt formations, because salt has higher thermal conductivity than rock and dissipates the heat more easily.) The problem can be eased by storing the waste above ground for a decade or so. This would allow the initially high rate of decay to decrease, thereby lowering the temperature that would be reached after encapsulation. Handled in this way, borosilicate glass would be an excellent encapsulation material for reactor waste that had been aged for a decade or so.

The other candidate is a synthetic rock made of mineral mixtures such as zirconolite and perovskite. These are very insoluble and, in their natural state, are known to have sequestered radioactive elements for hundreds of millions of years. They are crystalline, ceramic materials whose crystal structures allow radioactive atoms to be immobilized within them. They are not subject to devitrification, since they are already crystalline.

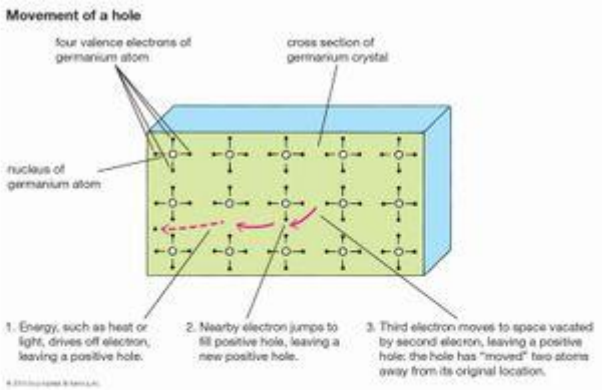
Once encapsulated, radioactive waste must be put into canisters that are corrosion-resistant. These can be made of nickel-steel alloys, but the best candidate so far is a titanium material containing small amounts of nickel and molybdenum and traces of carbon and iron. Even though they are meant to be buried in as dry an environment as possible, these metals are tested by immersing them in brine. Tests show that seawater at 250° C (480° F) would corrode away less than one micrometre (one-thousandth of a millimetre, or four ten-thousandths of an inch) of the surface of the titanium material (known as Ti code 12) per year. This remarkable performance is primarily the result of a tough, highly resistant oxide skin that forms on titanium when exposed to oxygen. It would take thousands of years for the canisters to be penetrated by corrosion.

In order to estimate the effectiveness of such waste disposal, it must be noted that the waste is highly radioactive and dangerous initially but that the danger decreases with time. Radioactivity decays to such levels that the danger is much less after a few hundred years, extremely low after 500 years, and negligible after 1,000 years. In order to breach the triple-barrier system, groundwater must migrate to the canister, eat it away, and then leach out the radioactive atoms from the encapsulating glass or ceramic. This is a process that most probably would take far longer than a single millennium. A careful application of materials science can make radioactive waste disposal safer than current disposal methods for other toxic wastes.

Photovoltaics

Photovoltaic systems are an attractive alternative to fossil or nuclear fuels for the generation of electricity. Sunlight is free, it does not use up an irreplaceable resource, and its conversion to electricity is nonpolluting. In fact, photovoltaics are now in use where power lines from utility grids are either not possible or do not exist, as in outer space or remote, nonurban locations.

The barrier to widespread use of sunlight to generate electricity is the cost of photovoltaic systems. The application of materials science is essential in efforts to lower the cost to levels that can compete with those for fossil or nuclear fuels.



electron hole: movement Movement of an electron hole in a crystal lattice.

The conversion of light to electricity depends on the electronic structure of solar cells with two or more layers of semiconductor material that can absorb photons, the primary energy packets of light. The photons raise the energy level of the electrons in the semiconductor, exciting some to jump from the lower-energy valence band to the higher-energy conduction band. The electrons in the conduction band and the holes they have left behind in the valence band are both mobile and can be induced to move by a voltage. The electron motion, and the movement of holes in the opposite direction, constitute an electric current. The force that drives electrons and holes through a circuit is created by the junction of two dissimilar semiconducting materials, one of which has a tendency to give up electrons and acquire holes (thereby becoming the positive, or *p*-type, charge carrier) while the other accepts electrons (becoming the negative, or *n*-type, carrier). The electronic structure that permits this is the band gap; it is equivalent to the energy required to move an electron from the lower band to the higher. The magnitude of this gap is important. Only photons with energy greater than that of the band gap can excite electrons from the valence band to the conduction band; therefore, the smaller the gap, the more efficiently light will be converted to electricity—since there is a greater range of light frequencies with sufficiently high energies. On the other hand, the gap cannot be too small, because the electrons and holes then find it easy to recombine, and a sizable current cannot be maintained.

The band gap defines the theoretical maximum efficiency of a solar cell, but this cannot be attained because of other materials factors. For each material there is an intrinsic rate of recombination of electrons and holes that removes their contribution to electric current. This recombination is enhanced by surfaces, interfaces, and crystal defects such as grain boundaries, dislocations, and impurities. Also, a fraction of the light is reflected by the cell's surface rather than being absorbed, and some can pass through the cell without exciting electrons to the conduction band.

Improvements in the trade-off between cell efficiency and cost are well illustrated by the preparation of silicon that is the basic material of current solar cells. Initially, high-purity silicon was grown from a silicon melt by slowly pulling out a seed crystal that grew by the accretion and slow solidification of the molten material. Known as the Czochralski process, this resulted in a high-purity, single-crystal ingot that was then sliced into wafers about 1 millimetre (0.04 inch) thick. Each wafer's surface was then "doped" with impurities to create *p*-type and *n*-type materials with a junction between them. Metal was then deposited to provide electrical leads, and the wafer was encapsulated to yield a cell about 100 millimetres in diameter. This was an expensive and time-consuming process; it has been much improved in a variety of ways. For example, high-purity silicon can be made at drastically reduced cost by chemically converting ordinary silicon to silane or trichlorosilane and then reducing it back to silicon. This silane process is capable of continuous operation at a high production rate and with low energy input. In order to avoid the cost and waste associated with sawing silicon into wafers, methods of directly drawing molten silicon into thin sheets or ribbons have been developed; these can produce crystalline, polycrystalline, or amorphous material. Another alternative is the manufacture of thin films on ceramic substrates—a process that uses much less silicon than other methods. Single-crystal silicon has a higher efficiency than other forms, but it is also much more expensive. The materials challenge is to find a combination of cost and efficiency that makes photovoltaic electricity economically possible.

Surface treatments that increase efficiency include deposition of antireflecting coatings, such as silicon nitride, on the front of the cell and highly reflective coatings on the rear. Thus, more of the light that strikes a cell actually enters it, and light that escapes out the back is reflected back into the cell. An ingenious surface treatment is part of the point contact method, in which the surface of the cell is not planar but microgrooved so that light is randomly reflected as it strikes the cell. This increases the amount of light that can be captured by the cell.

Louis A. Girifalco

Materials for ground transportation

The global effort to improve the efficiency of ground transportation vehicles, such as automobiles, buses, trucks, and trains, and thereby reduce the massive amounts of pollutants they emit, provides an excellent context within which to illustrate how materials science functions to develop new or better materials in response to critical human needs. For the automobile industry in particular, the story is a fascinating one in which the desire for lower vehicle weight, reduced emissions, and improved fuel economy has led to intense competition among aluminum, plastics, and steel companies for shares in the enormous markets involved (40 million to 50 million cars and trucks per year worldwide). In this battle, materials scientists have a key role to play because the success of their efforts to develop improved materials will determine the shape and viability of future automobiles.

Just how seriously suppliers to the industry view the need either to protect or to increase their share of these enormous markets is demonstrated by their establishing of special programs, consortia, or centres that are specifically designed to develop better alloys, plastics, or ceramics for automotive applications. For example, in the United States a program at the Aluminum Company of America (Alcoa) called the aluminum intensive vehicle (AIV), and a similar one at Reynolds Metals, were established to develop materials and processes for making automobile “space frames” consisting of aluminum-alloy rods and die-cast connectors joined by welding and adhesive bonding. Not to be outdone, another aluminum company, Alcan Aluminium Limited of Canada, in a program entitled aluminum structured vehicle technology (ASVT), began to investigate the construction of automobile unibodies from adhesively bonded aluminum sheet. The plastics industry, of course, has a powerful interest in replacing as many metal automobile components as possible, and in order to help bring this about a centre called D&S Plastics International was formed in the Detroit, Mich., area of the United States by three corporations. The specific aim of this centre was to develop materials and a process suitable for forming several connected panels or components (*e.g.,* body panels and bumper fascias) simultaneously out of different types of plastics. The centrepiece of the operation was a 4,000-ton co-injection press that could lead to cost reductions as great as 50 percent and thereby make the use of plastics for automotive applications more attractive.

In programs such as these, and in many more carried out by vendors and within the automobile companies themselves, materials scientists with specialized training in advanced metals, plastics, and ceramics have been leading a revolution in the automotive industry. The following sections describe specific needs that have been identified for improving the performance of automobiles and other ground-transportation vehicles, as well as approaches that materials scientists have taken in response to those needs.

Metals

Aluminum

Since aluminum has about one-third the density of steel, its substitution for steel in automobiles would seem to be a sensible approach to reducing weight and thereby increasing fuel economy and reducing harmful emissions. Such substitutions cannot be made, however, without due consideration of significant differences in other properties of the two materials. This is one important facet of the materials scientist's job—to help evaluate the suitability of a material for a given application based on how its properties balance against load and performance requirements specified by the design engineer. In this case (aluminum versus steel), it is instructive to consider the materials scientist's approach to evaluating the use of aluminum in automotive panels—such components as doors, hoods, trunk decks, and roofs that can make up more than 60 percent of a vehicle's weight.

Two primary properties of any metal are (1) its yield strength, defined as its ability to resist permanent deformation (such as a fender dent), and (2) its elastic modulus, defined as its ability to resist elastic or springy deflection like a drum head. By alloying, aluminum can be made to have a yield strength equal to a moderately strong steel and therefore to exhibit similar resistance to denting in an automobile panel. On the other hand, alloying does not normally affect the elastic modulus of metals significantly, so that automotive door panels or hoods made from aluminum alloys, all of which have approximately one-third the modulus of steel, would be floppy and suffer large deflections when buffeted by the wind, for example. From this point of view, aluminum would appear to be a marginal choice for body panels.

One might attempt to overcome this deficiency by increasing the thickness of the aluminum sheet stock to three times the thickness of the steel it is intended to replace. This, however, would simply increase the weight to roughly that of an equivalent steel structure and thus defeat the purpose of the exercise. Fortunately, as was elegantly demonstrated in 1980 by two British materials scientists, Michael Ashby and David Jones, when proper account is taken of the way an actual door panel deflects, constrained as it is by the door edges, it is possible to use aluminum sheet only slightly thicker than the steel it would replace and still achieve equivalent performance. The net result would be a weight savings of almost two-thirds by the substitution of aluminum for steel on such body components. This suggests that understanding the interrelationship between materials properties and structural design is an important factor in the successful application of materials science.

Another important activity of the materials scientist is that of alloy development, which in some cases involves designing alloys for very specific applications. For example, in Alcoa's AIV effort, materials scientists and engineers developed a special casting alloy for use as cast aluminum nodes (connecters) in their space frame design. Ordinarily, metal castings exhibit very little toughness, or ductility, and they are therefore prone to brittle fracture followed by catastrophic failure. Since the integrity of an automobile would be limited by having relatively brittle body components, a proprietary casting alloy and processing procedure were developed that provide a material of much greater ductility than is normally available in a casting alloy.

Many other advances in aluminum technology, brought about by materials scientists and design engineers, have led to a greater acceptance of aluminum in automobiles, trucks, buses, and even light rail vehicles. Among these are alloys for air-conditioner components that are designed to be chemically compatible with environmentally safer refrigerants and to withstand the higher pressures required by them. Also, alloys have been developed that combine good formability and corrosion resistance with the ability to achieve maximum strength without heat treating; these alloys develop their strength during the forming operation. As a consequence, the list of vehicles that contain significant quantities of aluminum substituted for steel has steadily grown. A milestone was reached in 1992 with a limited-edition Jaguar sports car that was virtually all aluminum, including the engine, adhesively bonded chassis, and skin. Somewhat less expensive and in full production were Honda's Acura NSX, containing more than 400 kilograms (900 pounds) of aluminum compared with about 70 kilograms for the average automobile, and General Motors' Saturn, with an aluminum engine block and cylinder heads. These vehicles and others took their place alongside the British Land Rover, which was built with all-aluminum body panels beginning in 1948—a choice dictated by a shortage of steel during World War II and continued by the manufacturer ever since.

Steel

While the goal of the aluminum and plastics industries is to achieve vehicle weight reductions by substituting their products for steel components, the goal of the steel industry is to counter such inroads with such innovative developments as high-strength, but inexpensive, "microalloyed" steels that achieve weight savings by thickness reductions. In addition, alloys have been developed that can be tempered (strengthened) in paint-baking ovens rather than in separate and expensive heat-treatment furnaces normally required for conventional steels.

The microalloyed steels, also known as high-strength low-alloy (HSLA) steels, are intermediate in composition between carbon steels, whose properties are controlled mainly by the amount of carbon they contain (usually less than 1 percent), and alloy steels, which derive their strength, toughness, and corrosion resistance primarily from other elements, including silicon, nickel, and manganese, added in somewhat larger amounts. Developed in the l960s and resurrected in the late 1970s to satisfy the need for weight savings through greater strength, the HSLA steels tend to be low in carbon with minute additions of titanium or vanadium, for example. Offering tensile strengths that can be triple the value of the carbon steels they are designed to replace (*e.g.,* 700 megapascals versus 200 megapascals), they have led to significant weight savings through thickness reductions—albeit at a slight loss of structural stiffness, because their elastic moduli are the same as other steels. They are considered to be quite competitive with aluminum substitutes for two reasons: they are relatively inexpensive (steel sells for one-half the price of aluminum on a per-unit-weight basis); and very little change in fabrication and processing procedures is needed in switching from carbon steel to HSLA steel, whereas major changes are usually required in switching to aluminum.

Bake-hardenable steels were developed specifically for the purpose of eliminating an expensive fabrication step—*i.e.,* the heat-treating furnace, where steels are imparted with their final strength. To do this, materials scientists have designed steels that can be strengthened in the same ovens used to bake body paint onto the part. These furnaces must operate at relatively low temperatures (170° C, or 340° F), so that special steels had to be developed that would achieve suitable strengths at heat-treatment temperatures very much below those normally employed (up to 600° C, or 1,100° F). Knowing that high-alloy steels would never be hardenable at such low temperatures, materials scientists focused their attention on carbon steels, but even here adequate strengths could not be obtained initially. Then in the 1980s scientists at the Japanese Sumitomo Metal Industries developed a steel containing nitrogen (a gas that constitutes three-quarters of the Earth's atmosphere) in addition to carbon and several other additives. Very high strengths (over 900 megapascals) and excellent toughness can be achieved on formed parts with this inexpensive addition after baking for 20 minutes at temperatures typical for a paint-baking operation.

Plastics and composites

The motive for replacing the metal components of cars, trucks, and trains with plastics is the expectation of large weight savings due to the large differences in density involved: plastics are one-sixth the weight of steel and one-half that of aluminum per unit volume. However, as in evaluating the suitability of replacing steel with aluminum, the materials scientist must compare other properties of the materials in order to determine whether the tradeoffs are reasonable. For two reasons, the likely conclusion would be that plastics simply are not suitable for this type of application: the strength of most plastics, such as epoxies and polyesters, is roughly one-fifth that of steel or aluminum; and their elastic modulus is one-sixtieth that of steel and one-twentieth that of aluminum. On this basis, plastics do not appear to be suitable for structural components. What, then, accounts for the successful use that has been made of them? The answer lies in efforts made over the years by materials scientists, polymer chemists, mechanical engineers, and production managers to combine relatively weak and low-stiffness resins with high-strength, high-modulus reinforcements, thereby making new materials called composites with much more suitable properties than plastics alone.

The reinforcements used in composites are generally chosen for their high strength and modulus, as might be expected, but economic considerations often force compromises. For example, carbon fibres have extremely high modulus values (up to five times that of steel) and therefore make excellent reinforcements. However, their cost precludes their extensive use in automobiles, trucks, and trains, although they are used regularly in the aerospace industry. More suitable for non-aerospace applications are glass fibres (whose modulus can approach 1.5 times that of aluminum) or, in somewhat special cases, a mixture of glass and carbon fibres.

The physical form and shape of the reinforcements vary greatly, depending on many factors. The most effective reinforcements are long fibres, which are employed either in the form of a woven cloth or as separate layers of unidirectional fibres stacked upon one another until the proper laminate thickness is achieved. The resin may be applied to the fibres or cloth before laying up, thus forming what are termed prepregs, or it may be added later by “wetting out” the fibres. In either case, the assembly is then cured, usually under pressure, to form the composite. This type of composite takes full advantage of the properties of the fibres and is therefore capable of yielding strong, stiff panels. Unfortunately, the labour involved in the lay-up operations and other factors make it very expensive, so that long-fibre reinforcement is used only sparingly in the automobile industry.

One attempt to avoid expensive hand lay-up operations involves chopped fibres that are employed in mat form, somewhat like felt, or as loose fibres that may be either blown into a mold or injected into a mold along with the resin. Another method does not use fibres at all; instead the reinforcement is in the form of small, high-modulus particles. These are the least expensive of all to process, since the particles are simply mixed into the resin, and the mixture is used in various types of molds. On the other hand, particles are the least efficient reinforcement material; as a consequence, property improvements are not outstanding.

In choosing the other major constituent in composites, the polymer matrix, one faces a somewhat daunting variety, including epoxies, polyimides, polyurethanes, and polyesters. Each has its advantages and disadvantages that must be evaluated in order to determine suitability for a particular application. Among the factors to be considered are cost, processing temperature (curing temperature if using a thermoset polymer and melting temperature if using a thermoplastic), flow properties in the molding operation, sag resistance during paint bake out, moisture resistance, and shelf life. The number of combinations of resins, reinforcements, production methods, and fibre-to-resin ratios is so challenging that materials scientists must join forces with polymer chemists and engineers from the design, production, and quality-control departments of the company in order to choose the right combination for the application.

Judging by the inroads that have been made in replacing metals with composites, it appears that technologists have been making the right choices. The introduction of fibreglass-reinforced plastic skins on General Motors' l953 Corvette sports car marked the first appearance of composites in a production model, and composites have continued to appear in automotive components ever since. In 1984, General Motors' Fiero was placed on the market with the entire body made from composites, and the Camaro/Firebird models followed with doors, roof panels, fenders, and other parts made of composites. Composites were also chosen for exterior panels in the Saturn, which appeared in 1990. In addition, they have had less visible applications—for example, the glass-reinforced nylon air-intake manifold on some BMW models.

Ceramics

Ceramics play an important role in engine efficiency and pollution abatement in automobiles and trucks. For example, one type of ceramic, cordierite (a magnesium aluminosilicate), is used as a substrate and support for catalysts in catalytic converters. It was chosen for this purpose because, along with many ceramics, it is lightweight, can operate at very high temperatures without melting, and conducts heat poorly (helping to retain exhaust heat for improved catalytic efficiency). In a novel application of ceramics, a cylinder wall was made of transparent sapphire (aluminum oxide) by General Motors' researchers in order to examine visually the internal workings of a gasoline engine combustion chamber. The intention was to arrive at improved understanding of combustion control, leading to greater efficiency of internal-combustion engines.

Another application of ceramics to automotive needs is a ceramic sensor that is used to measure the oxygen content of exhaust gases. The ceramic, usually zirconium oxide to which a small amount of yttrium has been added, has the property of producing a voltage whose magnitude depends on the partial pressure of oxygen surrounding the material. The electrical signal obtained from such a sensor is then used to control the fuel-to-air ratio in the engine in order to obtain the most efficient operation.

Because of their brittleness, ceramics have not been used as load-bearing components in ground-transportation vehicles to any great extent. The problem remains a challenge to be solved by materials scientists of the future.

John D. Venables

Materials for aerospace

The primary goal in the selection of materials for aerospace structures is the enhancement of fuel efficiency to increase the distance traveled and the payload delivered. This goal can be attained by developments on two fronts: increased engine efficiency through higher operating temperatures and reduced structural weight. In order to meet these needs, materials scientists look to materials in two broad areas—metal alloys and advanced composite materials. A key factor contributing to the advancement of these new materials is the growing ability to tailor materials to achieve specific properties.

Metals

Many of the advanced metals currently in use in aircraft were designed specifically for applications in gas-turbine engines, the components of which are exposed to high temperatures, corrosive gases, vibration, and high mechanical loads. During the period of early jet engines (from about 1940 to 1970), design requirements were met by the development of new alloys alone. But the more severe requirements of advanced propulsion systems have driven the development of novel alloys that can withstand temperatures greater than 1,000° C (1,800° F), and the structural performance of such alloys has been improved by developments in the processes of melting and solidification.

Melting and solidifying

Alloys are substances composed of two or more metals or of a metal and a nonmetal that are intimately united, usually by dissolving in each other when they are melted. The principal objectives of melting are to remove impurities and to mix the alloying ingredients homogeneously in the base metal. Major advances have been made with the development of new processes based on melting under vacuum (hot isostatic pressing), rapid solidification, and directional solidification.

In hot isostatic pressing, prealloyed powders are packed into a thin-walled, collapsible container, which is placed in a high-temperature vacuum to remove adsorbed gas molecules. It is then sealed and put in a press, where it is exposed to very high temperatures and pressures. The mold collapses and welds the powder together in the desired shape.

Molten metals cooled at rates as high as a million degrees per second tend to solidify into a relatively homogeneous microstructure, since there is insufficient time for crystalline grains to nucleate and grow. Such homogeneous materials tend to be stronger than the typical “grainy” metals. Rapid cooling rates can be achieved by “splat” cooling, in which molten droplets are projected onto a cold surface. Rapid heating and solidification can also be achieved by passing high-power laser beams over the material’s surface.

Unlike composite materials (see below Composites), grainy metals exhibit properties that are essentially the same in all directions, so they cannot be tailored to match anticipated load paths (*i.e.,* stresses applied in specific directions). However, a technique called directional solidification provides a certain degree of tailorability. In this process the temperature of the mold is precisely controlled to promote the formation of aligned stiff crystals as the molten metal cools. These serve to reinforce the component in the direction of alignment in the same fashion as fibres reinforce composite materials.

Alloying

These advances in processing have been accompanied by the development of new “superalloys.” Superalloys are high-strength, often complex alloys that are resistant to high temperatures and severe mechanical stress and that exhibit high surface stability. They are commonly classified into three major categories: nickel-based, cobalt-based, and iron-based. Nickel-based superalloys predominate in the turbine section of jet engines. Although they have little inherent resistance to oxidation at high temperatures, they gain desirable properties through the addition of cobalt, chromium, tungsten, molybdenum, titanium, aluminum, and niobium.

Aluminum-lithium alloys are stiffer and less dense than conventional aluminum alloys. They are also “superplastic,” owing to the fine grain size that can now be achieved in processing. Alloys in this group are appropriate for use in engine components exposed to intermediate to high temperatures; they can also be used in wing and body skins.

Titanium alloys, as modified to withstand high temperatures, are seeing increased use in turbine engines. They are also employed in airframes, primarily for military aircraft but to some extent for commercial planes as well.

Composites

While developments in metals have had an impact on engine design, there is a growing trend toward the application of composite materials to aerospace structures. One of the reasons for this is that alloys do not offer substantial weight savings, which is a primary advantage of composites. Indeed, advanced composites have been used most widely where saving mass results in either significantly improved performance or significantly lower life-cycle costs. The most extensive application, therefore, has been in satellite systems, military aircraft, radomes, helicopters, commercial transport aircraft, and general aviation.

Broadly defined, composites are materials with two or more distinct components that combine to yield characteristics superior to those of the individual constituents. Although this definition can apply to such ordinary building materials as plywood, concrete, and bricks, within the aerospace industry the term composite generally refers to the fibre-reinforced metal, polymer, and ceramic products that have come into use since World War II. These materials consist of fibres (such as glass, graphite, silicon carbide, or aramid) that are embedded in a matrix of, for example, aluminum, epoxy, or silicon nitride.

In the late 1950s a revolution in materials development occurred in response to the space program’s need for lightweight, thermally stable materials. Boron-tungsten filaments, carbon-graphite fibres, and organic aramid fibres proved to be strong, stiff, and light, but one problem with using them as fibres was that they were of limited value in any construction other than rope, which can bear loads in only one direction. Materials scientists needed to develop a way to make them useful under all loading conditions, and this led to the development of composites. While the structural value of a bundle of fibres is low, the strength of individual fibres can be harnessed if they are embedded in a matrix that acts as an adhesive, binding the fibres and lending solidity to the material. The matrix also protects the fibres from environmental stress and physical damage, which can initiate cracks. In addition, while the strength and stiffness of the composite remain largely a function of the reinforcing material—that is, the fibres—the matrix can contribute other properties, such as thermal and electrical conductivity and, most important, thermal stability. Finally, fibre-matrix combination reduces the potential for complete fracture. In a monolithic (or single) material, a crack, once started, generally continues to propagate until the material fails; in a composite, if one fibre in an assemblage fails, the crack may not extend to the other fibres, so the damage is limited.

Analyzing the peacock mantis shrimp's claws Why the peacock mantis shrimp's clubs can take a beating.
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To some extent, the composite-materials engineer is trying to mimic structures made spontaneously by plants and animals. A tree, for example, is made of a fibre-reinforced material whose strength is derived from cellulose fibres that grow in directions that match the weight of the branches. Similarly, many organisms naturally fabricate “bioceramics,” such as those found in shells, teeth, and bones. While the designers of composites for the aerospace industry would like to copy some of the features of bioceramics production—room-temperature processing and net-shape products, for example—they do not want to be constrained by slow processing methods and limited fibre and matrix material choices. In addition, unlike a mollusk, which has to produce only one shell, the composites manufacturer has to use rapid, repeatable processing methods that can fabricate hundreds or even thousands of parts.

Modern composites are generally classified into three categories according to the matrix material: polymer, metal, or ceramic. Since polymeric materials tend to degrade at elevated temperatures, polymer-matrix composites (PMCs) are restricted to secondary structures in which operating temperatures are lower than 300° C (570° F). For higher temperatures, metal-matrix and ceramic-matrix composites are required.

Polymer-matrix composites

PMCs are of two broad types, thermosets and thermoplastics. Thermosets are solidified by irreversible chemical reactions, in which the molecules in the polymer "cross-link," or form connected chains. The most common thermosetting matrix materials for high-performance composites used in the aerospace industry are the epoxies. Thermoplastics, on the other hand, are melted and then solidified, a process that can be repeated numerous times for reprocessing. Although the manufacturing technologies for thermoplastics are generally not as well developed as those for thermosets, thermoplastics offer several advantages. First, they do not have the shelf-life problem associated with thermosets, which require freezer storage to halt the irreversible curing process that begins at room temperature. Second, they are more desirable from an environmental point of view, as they can be recycled. They also exhibit higher fracture toughness and better resistance to solvent attack. Unfortunately, thermoplastics are more expensive, and they generally do not resist heat as well as thermosets; however, strides are being made in developing thermoplastics with higher melting temperatures. Overall, thermoplastics offer a greater choice of processing approaches, so that the process can be determined by the scale and rate of production required and by the size of the component.

A variety of reinforcements can be used with both thermoset and thermoplastic PMCs, including particles, whiskers (very fine single crystals), discontinuous (short) fibres, continuous fibres, and textile preforms (made by braiding, weaving, or knitting fibres together in specified designs). Continuous fibres are more efficient at resisting loads than are short ones, but it is more difficult to fabricate complex shapes from materials containing continuous fibres than from short-fibre or particle-reinforced materials. To aid in processing, most high-performance composites are strengthened with filaments that are bundled into yarns. Each yarn, or tow, contains thousands of filaments, each of which has a diameter of approximately 10 micrometres (0.01 millimetre, or 0.0004 inch).

Depending on the application and on the type of load to be applied to the composite part, the reinforcement can be random, unidirectional (aligned in a single direction), or multidirectional (oriented in two or three dimensions). If the load is uniaxial, the fibres are all aligned in the load direction to gain maximum benefit of their stiffness and strength. However, for multidirectional loading (for example, in aircraft skins), the fibres must be oriented in a variety of directions. This is often accomplished by stacking layers (or lamina) of continuous-fibre systems.

The most common form of material used for the fabrication of composite structures is the preimpregnated tape, or "prepreg." There are two categories of prepreg: tapes, generally 75 millimetres (3 inches) or less in width, intended for fabrication in automated, computer-controlled tape-laying machines; and "broad goods," usually several metres in dimension, intended for hand lay-up and large sheet applications. To make prepregs, fibres are subjected to a surface treatment so that the resin will adhere to them. They are then placed in a resin bath and rolled into tapes or sheets.

To fabricate the composite, the manufacturer "lays up" the prepreg according to the reinforcement needs of the application. This has traditionally been done by hand, with successive layers of a broad-goods laminate stacked over a tool in the shape of the desired part in such a way as to accommodate the anticipated loads. However, efforts are now being directed toward automated fibre-placement methods in order to reduce costs and ensure quality and repeatability. Automated fibre-placement processes fall into two categories, tape laying and filament winding. The tape-laying process involves the use of devices that control the placement of narrow prepreg tapes over tooling with the contours of the desired part and along paths prescribed by the design requirements of the structure. The width of the tape determines the "sharpness" of the turns required to place the fibres in the prescribed direction—*i.e.*, wide tapes are used for gradual turns, while narrow tapes are required for the sharp turns associated with more complex shapes.

Filament winding uses the narrowest prepreg unit available—the yarn, or tow, of impregnated filaments. In this process, the tows are wound in prescribed directions over a rotating mandrel in the shape of the part. Successive layers are added until the required thickness is reached. Although filament winding was initially limited to geodesic paths (*i.e.,* winding the fibres along the most direct route between two points), the process is now capable of fabricating complex shapes through the use of robots.

For thermosetting polymers, the structure generated by either tape laying or filament winding must undergo a second manipulation in order to solidify the polymer through a curing reaction. This is usually accomplished by heating the completed structure in an autoclave, or oven. Thermoplastic systems offer the advantage of on-line consolidation, so that the high energy and capital costs associated with the curing step can be eliminated. For these systems, prepreg can be locally melted, consolidated, and cooled at the point of contact so that a finished structure is produced. A variety of energy sources are used to concentrate heat at the point of contact, including hot-gas torches, infrared light, and laser beams.

Pultrusion, the only truly continuous process for manufacturing parts from PMCs, is economical but limited to the production of beamlike shapes. On a pultrusion line, fibres and the resin are pushed through a heated die, or shaping tool, at one end, then cooled and pulled out at the other end. This process can be applied to both thermoplastic and thermoset polymers.

Resin transfer molding, or RTM, is a composites processing method that offers a high potential for tailorability but is currently limited to low-viscosity (easily flowing) thermosetting polymers. In RTM, a textile preform—made by braiding, weaving, or knitting fibres together in a specified design—is placed into a mold, which is then closed and injected with a resin. After consolidation, the mold is opened and the part removed. Preforms can be made in a wide variety of architectures, and several can be joined together during the RTM process to form a multi-element preform offering reinforcement in specific areas and load directions.

The similarity of meltable thermoplastic polymers to metals has prompted the extension of techniques used in metalworking. Sheet forming, used since the 19th century by metallurgists, is now applied to the processing of thermoplastic composites. In a typical thermoforming process, the sheet stock, or preform, is heated in an oven. At the forming temperature, the sheet is transferred into a forming system, where it is forced to conform to a tool, with a shape that matches the finished part. After forming, the sheet is cooled under pressure and then removed. Stretch forming, a variation on thermoplastic sheet forming, is specifically designed to take advantage of the extensibility, or ability to be stretched, of thermoplastics reinforced with long, discontinuous fibres. In this process, a straight preconsolidated beam is heated and then stretched over a shaped tool to introduce curvature. The specific advantage of stretch forming is that it provides an automated way to achieve a very high degree of fibre-orientation control in a wide range of part sizes.

Metal-matrix and ceramic-matrix composites

The requirement that finished parts be able to operate at temperatures high enough to melt or degrade a polymer matrix creates the need for other types of matrix materials, often metals. Metal matrices offer not only high-temperature resistance but also strength and ductility, or "bendability," which increases toughness. The main problems with metal-matrix composites (MMCs) are that even the lightest metals are heavier than polymers, and they are very complex to process. MMCs can be used in such areas as the skin of a hypersonic aircraft, but on wing edges and in engines temperatures often exceed the melting point of metals. For the latter applications, ceramic-matrix composites (CMCs) are seeing increasing use, although the technology for CMCs is less mature than that for PMCs. Ceramics consist of alumina, silica, zirconia, and other elements refined from fine earth and sand or of synthetic materials, such as silicon nitride or silicon carbide. The desirable properties of ceramics include superior heat resistance and low abrasive and corrosive properties. Their primary drawback is brittleness, which can be reduced by reinforcing with fibres or whiskers. The reinforcement material can be a metal or another ceramic.

Unlike polymers and metals, which can be processed by techniques that involve melting (or softening) followed by solidification, high-temperature ceramics cannot be melted. They are generally produced by some variation of sintering, a technique that renders a combination of materials into a coherent mass by heating to high temperatures without complete melting. If continuous fibres or textile weaves (as opposed to short fibres or whiskers) are involved, sintering is preceded by impregnating the assembly of fibres with a slurry of ceramic particles dispersed in a liquid. A major benefit of using CMCs in aircraft engines is that they allow higher operating temperatures and thus greater combustion efficiency, leading to reduced fuel consumption. An additional benefit is derived from the low density of CMCs, which translates into substantial weight savings.

Other advanced composites

Carbon-carbon composites are closely related to CMCs but differ in the methods by which they are produced. Carbon-carbon composites consist of semicrystalline carbon fibres embedded in a matrix of amorphous carbon. The composite begins as a PMC, with semicrystalline carbon fibres impregnated with a polymeric phenolic resin. The resin-soaked system is heated in an inert atmosphere to pyrolyze, or char, the polymer to a carbon residue. The composite is re-impregnated with polymer, and the pyrolysis is repeated. Continued repetition of this impregnation/pyrolysis process yields a structure with minimal voids. Carbon-carbon composites retain their strength at 2,500° C (4,500° F) and are used in the nose cones of reentry vehicles. However, because they are vulnerable to oxidation at such high temperatures, they must be protected by a thin layer of ceramic.

While materials research for aerospace applications has focused largely on mechanical properties such as stiffness and strength, other attributes are important for use in space. Materials are needed with a near-zero coefficient of thermal expansion; in other words, they have to be thermally stable and should not expand and contract when exposed to extreme changes in temperature. A great deal of research is focused on developing such materials for high-speed civilian aircraft, where thermal cycling is a major issue. High-toughness materials and nonflammable resin composite systems are also under investigation to improve the safety of aircraft interiors.

Efforts are also being directed toward the development of “smart,” or responsive, materials. Representing another attempt to mimic certain characteristics of living organisms, smart materials, with their built-in sensors and actuators, would react to their external environment by bringing on a desired response. This would be done by linking the mechanical, electrical, and magnetic properties of these materials. For example, piezoelectric materials generate an electrical current when they are bent; conversely, when an electrical current is passed through these materials, they stiffen. This property can be used to suppress vibration: the electrical current generated during vibration could be detected, amplified, and sent back, causing the material to stiffen and stop vibrating.

R.L. McCulloughDiane S. Kukich

Materials for computers and communications

Understand how researchers are creating wrinkled surfaces with precise sizes and controlled patterns for use in various structures Creating wrinkled surfaces with precisely controlled sizes and patterns for use in various structures.(more)
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The basic function of computers and communications systems is to process and transmit information in the form of signals representing data, speech, sound, documents, and visual images. These signals are created, transmitted, and processed as moving electrons or photons, and so the basic materials groups involved are classified as electronic and photonic. In some cases, materials known as optoelectronic bridge these two classes, combining abilities to interact usefully with both electrons and photons.

Among the electronic materials are various crystalline semiconductors; metalized film conductors; dielectric films; solders; ceramics and polymers formed into substrates on which circuits are assembled or printed; and gold or copper wiring and cabling.

Photonic materials include a number of compound semiconductors designed for light emission or detection; elemental dopants that serve as photonic performance-control agents; metal- or diamond-film heat sinks; metalized films for contacts, physical barriers, and bonding; and silica glass, ceramics, and rare earths for optical fibres.

Electronic materials

Between 1955 and 1990, improvements and innovations in semiconductor technology increased the performance and decreased the cost of electronic materials and devices by a factor of one million—an achievement unparalleled in the history of any technology. Along with this extraordinary explosion of technology has come an exponentially upward spiral of the capital investment necessary for manufacturing operations. In order to maintain cost-effectiveness and flexibility, radical changes in materials and manufacturing operations will be necessary.

Semiconductor crystals

Silicon

Bulk semiconductor silicon for the manufacture of integrated circuits (sometimes referred to as electronic-grade silicon) is the purest material ever made commercially in large quantities. One of the most important factors in preparing this material is control of such impurities as boron, phosphorus, and carbon (not to be confused with the dopants added later during circuit production). For the ultimate levels of integrated-circuit design, stray contaminant atoms must constitute less than 0.1 part per trillion of the material.

For fabrication into integrated circuits, bulk semiconductor silicon must be in the form of a single-crystal material with high crystalline perfection and the desired charge-carrier concentration. The size of the silicon ingot, or boule, has been scaled up in recent years, in order to provide wafers of increasing diameter that are demanded by the economics of integrated-circuit manufacturing. Most commonly, a 60-kilogram (130-pound) charge is grown to an ingot with a diameter of 200 millimetres (8 inches), but the semiconductor industry will soon require ingots as large as 300 millimetres. The ingots are then converted into wafers by machining and chemical processes.

III–V compounds

Although silicon is by far the most commonly used crystal material for integrated circuits, a significant volume of semiconductor devices and circuits employs III–V technology, so named because it is based on crystalline compounds formed by combining metallic elements from column III and nonmetallic elements from column V of the periodic table of chemical elements. When the elements are gallium and arsenic, the semiconductor is called gallium arsenide, or GaAs. However, other elements such as indium, phosphorus, and aluminum are often used in the compound to achieve specific performance characteristics.

For electronic applications, the III–V semiconductors offer the basic advantage of higher electron mobility, which translates into higher operating speeds. In addition, devices made with III–V compounds provide lower voltage operation for specific functions, radiation hardness (especially important for satellites and space vehicles), and semi-insulating substrates (avoiding the presence of parasitic capacitance in switching devices).

III–V materials are more difficult to handle than silicon, and a III–V wafer or substrate usually is less than half the size of a silicon wafer. In addition, a gallium arsenide wafer entering the processing facility can be expected to cost 10 to 20 times as much as a silicon wafer, although that cost difference narrows somewhat after fabrication, packaging, and testing. Nevertheless, there is one major characteristic of III–V materials with which silicon cannot compete: a III–V compound can be tailored to generate or detect photons of a specific wavelength. For example, an indium gallium arsenide phosphide (InGaAsP) laser can generate radiation at 1.55 micrometres to carry digitally coded information streams. (See below Photonic materials.) This means that a III–V component can fill both electronic and photonic functions in the same integrated circuit.

Photoresist films

Patterning polished wafers with an integrated circuit requires the use of photoresist materials that form thin coatings on the wafer before each step of the photolithographic process. Modern photoresists are polymeric materials that are modified when exposed to radiation (either in the form of visible, ultraviolet, or X-ray photons or in the form of energetic electron beams). A photoresist typically contains a photoactive compound (PAC) and an alkaline-soluble resin. The PAC, mixed into the resin, renders it insoluble. This mixture is coated onto the semiconductor wafer and is then exposed to radiation through a “mask” that carries the desired pattern. Exposed PAC is converted into an acid that renders the resin soluble, so that the resist can be dissolved and the exposed substrate beneath it chemically etched or metallically coated to match the circuit design.

Besides practical properties such as shelf life, cost, and availability, the key properties of a photoresist include purity, etching resistance, resolution, contrast, and sensitivity. As the feature sizes of integrated circuits shrink in each successive generation of microchips, photoresist materials are challenged to handle shorter wavelengths of light. For example, the photolithography of current designs (with features that have shrunk to less than one micrometre) is based on ultraviolet radiation in the wavelength range of 365 to 436 nanometres, but, in order to define accurately the smaller features of future microchips (less than 0.25 micrometre), shorter wavelengths will be necessary. The problem here is that electromagnetic radiation in such frequency regions is weaker. One solution is to use the chemically amplified photoresist, or CAMP. The sensitivity of a photoresist is measured by its quantum efficiency, or the number of chemical events that occur when a photon is absorbed by the material. In CAMP material, the number of events is dramatically increased by subsequent chemical reactions (hence the amplification), which means that less light is needed to complete the process.

Electric connections

The performance of today's electronic systems (and photonic systems as well) is limited significantly by interconnection technology, in which components and subsystems are linked by conductors and connectors. Currently, very fine gold or copper wiring, as thin as 30 micrometres, is used to carry electric current to and from the many pads along the sides or ends of a microchip to other components on a circuit board. The capacitance involved in such circuitry slows down the flow of electrons and, hence, of information. However, by integrating several chips into a single multichip module, in which the chips are connected on a shared substrate by various conducting materials (such as metalized film), the speed of information flow can be increased, thus improving the assembly's performance. Ideally, all the chips in a single module would be fabricated simultaneously on the same wafer, but in practice this is not feasible: Silicon crystal manufacture is still subject to an average of one flaw per wafer, meaning that at least one of the many chips cut from each wafer is scrapped. If the whole wafer area were dedicated to a single multifunction assembly, that one flaw would scrap the entire module. Multichip modules are therefore made up of as many as five microchips bonded to a silicon or ceramic substrate on which resistors and capacitors have been constructed with thin films. Typical materials used in a multichip module include the substrate; gold paste conductors applied in an additive process resembling silk screen printing; vitreous glazes to insulate the gold paste conductors from subsequent film layers; a series of thin films made with tantalum nitride, titanium, palladium, and plated gold; and a final package of silicone rubber.

Packaging materials

Several major types of packaging material are used by the electronics industry, including ceramic, refractory glass, premolded plastic, and postmolded plastic. Ceramic and glass packages cost more than plastic packages, so they make up less than 10 percent of the worldwide total. However, they provide the best protection for complex chips. Premolded plastic packages account for only a small but important fraction of the market, since they are required for packaging devices with many leads. Most plastic packages are postmolded, meaning that the package body is molded over the assembly after the microchip has been attached to the fan-out pattern.

Precursors

The starting materials for most semiconductor devices are volatile and ultrapure gaseous derivatives of various organic and inorganic precursors. Many of them are toxic, and many will ignite spontaneously in the atmosphere. These gases are transported in high-pressure cylinders from the plant where they were made to the site where they will be used. One possible method of replacing these precursors with materials that are environmentally safe is known as in situ synthesis. In this method, dangerous reagents would be generated on demand in only the desired quantities, instead of being shipped cross-country and stored until needed at the semiconductor processing plant.

Photonic materials

Computers and communications systems have been dominated by electronic technology since their beginnings, but photonic technology is making serious inroads throughout the information movement and management systems with such devices as lasers, light-emitting diodes, photodetecting diodes, optical switches, optical amplifiers, optical modulators, and optical fibres. Indeed, for long-distance terrestrial and transoceanic transmission of information, photonics has almost completely displaced electronics.

Crystalline materials

The light detectors and generators listed above are actually optoelectronic, because they link photonic and electronic systems. They employ the III–V compound semiconductors described above, many of them characterized by their band gaps—*i.e.,* the energy minimum of the electron conduction band and the energy maximum of hole valence bands occur at the same location in the momentum space, allowing electrons and holes to recombine and radiate photons efficiently. (By contrast, the conduction band minimum and the valence band maximum in silicon have dissimilar momenta, and therefore the electrons and holes cannot recombine efficiently.) Among the important compounds are gallium arsenide, aluminum gallium arsenide, indium gallium arsenide phosphide, indium phosphide, and aluminum indium arsenide.

Fabricating a single crystal from these combinations of elements is far more difficult than creating a single crystal of electronic-grade silicon. Special furnaces are required, and the process can take several days. Notwithstanding the precision involved, the sausage-shaped boule is less than half the diameter of a silicon ingot and is subject to a much higher rate of defects. Researchers are continuously seeking ways to reduce the thermal stresses that are primarily responsible for dislocations in the III–V crystal lattice that cause these defects. The purity and structural perfection of the final single-crystal substrates affect the qualities of the crystalline layers that are grown on them and the regions that are diffused or implanted in them during the manufacture of photonic devices.

Epitaxial layers

For the efficient emission or detection of photons, it is often necessary to constrain these processes to very thin semiconductor layers. These thin layers, grown atop bulk semiconductor wafers, are called epitaxial layers because their crystallinity matches that of the substrate even though the composition of the materials may differ—*e.g.,* gallium aluminum arsenide (GaAlAs) grown atop a gallium arsenide substrate. The resulting layers form what is called a heterostructure. Most continuously operating semiconductor lasers consist of heterostructures, a simple example consisting of 1000-angstrom thick gallium arsenide layers sandwiched between somewhat thicker (about 10000 angstroms) layers of gallium aluminum arsenide—all grown epitaxially on a gallium arsenide substrate. The sandwiching and repeating of very thin layers of a semiconductor between layers of a different composition allow one to modify the band gap of the sandwiched layer. This technique, called band-gap engineering, permits the creation of semiconductor materials with properties that cannot be found in nature. Band-gap engineering, used extensively with III–V compound semiconductors, can also be applied to elemental semiconductors such as silicon and germanium.

The most precise method of growing epitaxial layers on a semiconducting substrate is molecular-beam epitaxy (MBE). In this technique, a stream or beam of atoms or molecules is effused from a common source and travels across a vacuum to strike a heated crystal surface, forming a layer that has the same crystal structure as the substrate. Variations of MBE include elemental-source MBE, hydride-source MBE, gas-source MBE, and metal-organic MBE. Other approaches to epitaxial growth are liquid-phase epitaxy (LPE) or chemical vapour deposition (CVD). The latter method includes hydride CVD, trichloride CVD, and metal-organic CVD.

Normally, epitaxial layers are grown on flat surfaces, but scientists are searching for an economical and reliable method of growing epitaxial material on nonplanar structures—for example, around the “mesas” or “ridges” or in the “tubs” or “channels” that are etched into the surface of semiconducting devices. Nonplanar epitaxy is considered necessary for producing monolithic integrated optical devices or all-photonic switches and logic elements, but mastery of this method requires better understanding of the surface chemistry and surface dynamics of epitaxial growth.

Optical switching

Research in this area is driven by the need to switch data streams of higher and higher speed efficiently as customers for computer and communications services demand transmission and switching rates far higher than can be provided by a purely electronic system. Thanks to developments in semiconductor lasers and detectors (described above Epitaxial layers) and in optical fibres (described below Optical transmission), transmission at the desired high speeds has become possible. However, the switching of optical data streams still requires converting the data from the optical to the electronic domain, subjecting them to electronic switching and to manipulation inside the switching apparatus, and then reconverting the switched and reconfigured data into the optical domain for transmission over optical fibres. Electronic switching therefore is seen as the principal barrier to achieving higher switching speeds. One approach to solving this problem would be to introduce optics inside digital switching machines. Known as free-space photonics, this approach would involve such devices as semiconductor lasers or light-emitting diodes (LEDs), optical modulators, and photodetectors—all of which would be integrated into systems combined with electronic components.

One commercially available device for photonic switching is the quantum-well self-electro-optic-effect device, or SEED. The key concept for this device is the use of quantum wells. These structures consist of many thin layers of two different semiconductor materials. Individual layers are typically 10 nanometres (about 40 atoms) thick, and 100 layers are used in a device about 1 micrometre thick. When a voltage is applied across the layers, the transmission of photons through the quantum wells changes significantly, in effect creating an optical modulator—an essential component of any photonic circuit. Variations on the SEED concept are the symmetric SEED (S-SEED) and the field-effect transistor SEED. Neighbouring S-SEEDs could be connected by pairs of back-to-back quantum-well photodiodes, and commercially sized interconnection networks could be built by using free-space photonic interconnections between two-dimensional arrays of switching nodes. However, even this type of free-space optical interconnection technology would only enhance and extend electronic technology, not replace it.

The move of optoelectronic and photonic integrated circuits out of the research laboratory and into the marketplace has been made possible by the availability of high-quality epitaxial growth techniques for building up lattice-matched crystalline layers of indium gallium arsenide phosphide and indium phosphide (InGaAsP/InP). This III–V compound system is central to the light emitters and detectors used in the 1.3-micrometre and 1.5-micrometre wavelength ranges at which optical fibre has very low transmission loss.

Optical transmission

As the rates of transmission are increased from millions of bits (megabits) per second to billions of bits (gigabits) per second, commercially available lasers encounter a physical limitation called "chirping," in which the optical frequency of the laser begins to waver during a pulse. Future systems, which may require from 2.4 to 30 gigabits per second, are probably going to be based on the use of a continuously operating distributed-feedback laser, whose output will be modulated in intensity by passing it through a modulator. This device consists of a crystal substrate of lithium niobate onto which a titanium channel is diffused to function as a light guide. The signal is encoded onto the light beam via a microwave radio-frequency feed through neighbouring channels in the coupler. Such a device is used only at the transmitter end of the optical path.

Both communications and computer systems rely on silica glass fibres to transmit light signals from lasers and LEDs. For long-distance transmission, optical-fibre cables are usually equipped with electro-optical repeater assemblies approximately every 100 kilometres. A new approach, called optical amplifiers, has been developed for deployment in transoceanic fibre-optic cables. Unlike traditional repeaters, optical amplifiers work by adding photons to a light signal without changing it to an electrical signal and without changing its bit-rate. Since they can be used at any desired transmission bit-rate, a transoceanic cable equipped with these devices can be upgraded to higher bit-rates simply by changing the lasers and photodiodes at each end. No retrofitting of higher bit-rate amplifiers is necessary.

The optical amplifier is a module containing a semiconductor pump laser and a short length of optical fibre whose core has been doped with less than 0.1 percent erbium, an optically active rare-earth element. The pump laser is powered by an electrical conductor that runs the length of the cable. The amplifier functions by converting the optical energy generated by the pump source into signal photon energy. When a signal-carrying stream of laser pulses passes through the optical amplifier, it is combined with the pump light through a wavelength division multiplexer located in the module. The combined signal is fed through the erbium-doped fibre length, where the excited erbium ions contribute photons coherently to the signal. The amplified signal is then fed to the next section of cable for transmission to the next optical amplifier, perhaps 200 to 300 kilometres away.

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Materials for medicine

The treatment of many human disease conditions requires surgical intervention in order to assist, augment, sustain, or replace a diseased organ, and such procedures involve the use of materials foreign to the body. These materials, known as biomaterials, include synthetic polymers and, to a lesser extent, biological polymers, metals, and ceramics. Specific applications of biomaterials range from high-volume products such as blood bags, syringes, and needles to more challenging implantable devices designed to augment or replace a diseased human organ. The latter devices are used in cardiovascular, orthopedic, and dental applications as well as in a wide range of invasive treatment and diagnostic systems. Many of these devices have made possible notable clinical successes. For example, in cardiovascular applications, thousands of lives have been saved by heart valves, heart pacemakers, and large-diameter vascular grafts, and orthopedic hip-joint replacements have shown great long-term success in the treatment of patients suffering from debilitating joint diseases. With such a tremendous increase in medical applications, demand for a wide range of biomaterials grows by 5 to 15 percent each year. In the United States the annual market for surgical implants exceeds $10 billion, approximately 10 percent of world demand.

Nevertheless, applications of biomaterials are limited by biocompatibility, the problem of adverse interactions arising at the junction between the biomaterial and the host tissue. Optimizing the interactions that occur at the surface of implanted biomaterials represents the most significant key to further advances, and an excellent basis for these advances can be found in the growing understanding of complex biological materials and in the development of novel biomaterials custom-designed at the molecular level for specific medical applications.

This section describes biomaterials that are used in medicine, with emphasis on polymer materials and on the challenges associated with implantable devices used in the cardiovascular and orthopedic areas.

General requirements of biomaterials

Research on developing new biomaterials is an interdisciplinary effort, often involving collaboration among materials scientists and engineers, biomedical engineers, pathologists, and clinicians to solve clinical problems. The design or selection of a specific biomaterial depends on the relative importance of the various properties that are required for the intended medical application. Physical properties that are generally considered include hardness, tensile strength, modulus, and elongation; fatigue strength, which is determined by a material's response to cyclic loads or strains; impact properties; resistance to abrasion and wear; long-term dimensional stability, which is described by a material's viscoelastic properties; swelling in aqueous media; and permeability to gases, water, and small biomolecules. In addition, biomaterials are exposed to human tissues and fluids, so that predicting the results of possible interactions between host and material is an important and unique consideration in using synthetic materials in medicine. Two particularly important issues in biocompatibility are thrombosis, which involves blood coagulation and the adhesion of blood platelets to biomaterial surfaces, and the fibrous-tissue encapsulation of biomaterials that are implanted in soft tissues.

Poor selection of materials can lead to clinical problems. One example of this situation was the choice of silicone rubber as a poppet in an early heart valve design. The silicone absorbed lipid from plasma and swelled sufficiently to become trapped between the metal struts of the valve. Another unfortunate choice as a biomaterial was Teflon (trademark), which is noted for its low coefficient of friction and its chemical inertness but which has relatively poor abrasion resistance. Thus, as an occluder in a heart valve or as an acetabular cup in a hip-joint prosthesis, Teflon may eventually wear to such an extent that the device would fail. In addition, degradable polyesterurethane foam was abandoned as a fixation patch for breast prostheses, because it offered a distinct possibility for the release of carcinogenic by-products as it degraded.

Besides their constituent polymer molecules, synthetic biomaterials may contain several additives, such as unreacted monomers and catalysts, inorganic fillers or organic plasticizers, antioxidants and stabilizers, and processing lubricants or mold-release agents on the material's surface. In addition, several degradation products may result from the processing, sterilization, storage, and ultimately implantation of a device. Many additives are beneficial—for example, the silica filler that is indispensable in silicone rubber for good mechanical performance or the antioxidants and stabilizers that prevent premature oxidative degradation of polyetherurethanes. Other additives, such as pigments, can be eliminated from biomedical products. Indeed, a "medical-grade" biomaterial is one that has had nonessential additives and potential contaminants excluded or eliminated from the polymer. In order to achieve this grade, the polymer may need to be solvent-extracted before use, thereby eliminating low-molecular-weight materials. Generally, additives in polymers are regarded with extreme suspicion, because it is often the additives rather than the constituent polymer molecules that are the source of adverse biocompatibility.

Polymer biomaterials

The majority of biomaterials used in humans are synthetic polymers such as the polyurethanes or Dacron (trademark; chemical name polyethylene terephthalate), rather than polymers of biological origin such as proteins or polysaccharides. The properties of common synthetic biomaterials vary widely, from the soft and delicate water-absorbing hydrogels made into contact lenses to the resilient elastomers found in short- and long-term cardiovascular devices or the high-strength acrylics used in orthopedics and dentistry. The properties of any material are governed by its chemical composition and by the intra- and intermolecular forces that dictate its molecular organization. Macromolecular structure in turn affects macroscopic properties and, ultimately, the interfacial behaviour of the material in contact with blood or host tissues.

Since the properties of each material are dependent on the chemical structure and macromolecular organization of its polymer chains, an understanding of some common structural features of various polymers provides considerable insight into their properties. Compared with complex biological molecules, synthetic polymers are relatively simple; often they comprise only one type of repeating subunit, analogous to a polypeptide consisting of just one repeating amino acid. On the basis of common structures and properties, synthetic polymers are classified into one of three categories: elastomers, which include natural and synthetic rubbers; thermoplastics; and thermosets. The properties that provide the basis for this classification include molecular weight, cross-link density, percent crystallinity, thermal transition temperature, and bulk mechanical properties.

Elastomers

Elastomers, which include rubber materials, have found wide use as biomaterials in cardiovascular and soft-tissue applications owing to their high elasticity, impact resistance, and gas permeability. Applications of elastomers include flexible tubing for pacemaker leads, vascular grafts, and catheters; biocompatible coatings and pumping diaphragms for artificial hearts and left-ventricular assist devices; grafts for reconstructive surgery and maxillofacial operations; wound dressings; breast prostheses; and membranes for implantable biosensors.

Elastomers are typically amorphous with low cross-link density (although linear polyurethane block copolymers are an important exception). This gives them low to moderate modulus and tensile properties as well as high elasticity. For example, elastomeric devices can be extended by 100 to 1,000 percent of their initial dimensions without causing any permanent deformation to the material. Silicone rubbers such as Silastic (trademark), produced by the American manufacturer Dow Corning, Inc., are cross-linked, so that they cannot be melted or dissolved—although swelling may occur in the presence of a good solvent. Such properties contrast with those of the linear polyurethane elastomers, which consist of soft polyether amorphous segments and hard urethane-containing glassy or crystalline segments. The two segments are incompatible at room temperature and undergo microphase separation, forming hard domains dispersed in an amorphous matrix. A key feature of this macromolecular organization is that the hard domains serve as physical cross-links and reinforcing filler. This results in elastomeric materials that possess relatively high modulus and extraordinary long-term stability under sustained cyclic loading. In addition, they can be processed by methods common to thermoplastics.

Thermoplastics

Many common thermoplastics, such as polyethylene and polyester, are used as biomaterials. Thermoplastics usually exhibit moderate to high tensile strength (5 to 1,000 megapascals) with moderate elongation (2 to 100 percent), and they undergo plastic deformation at high strains. Thermoplastics consist of linear or branched polymer chains; consequently, most can undergo reversible melt-solid transformation on heating, which allows for relatively easy processing or reprocessing. Depending on the structure and molecular organization of the polymer chains, thermoplastics may be amorphous (*e.g.,* polystyrene), semicrystalline (*e.g.,* low-density polyethylene), or highly crystalline (*e.g.,* high-density polyethylene), or they may be processed into highly crystalline textile fibres (*e.g.,* polyester Dacron).

Some thermoplastic biomaterials, such as polylactic acid and polyglycolic acid, are polymers based on a repeating amino acid subunit. These polypeptides are biodegradable, and, along with biodegradable polyesters and polyorthoesters, they have applications in absorbable sutures and drug-release systems. The rate of biodegradation in the body can be adjusted by using copolymers. These are polymers that link two different monomer subunits into a single polymer chain. The resultant biomaterial exhibits properties, including biodegradation, that are intermediate between the two homopolymers.

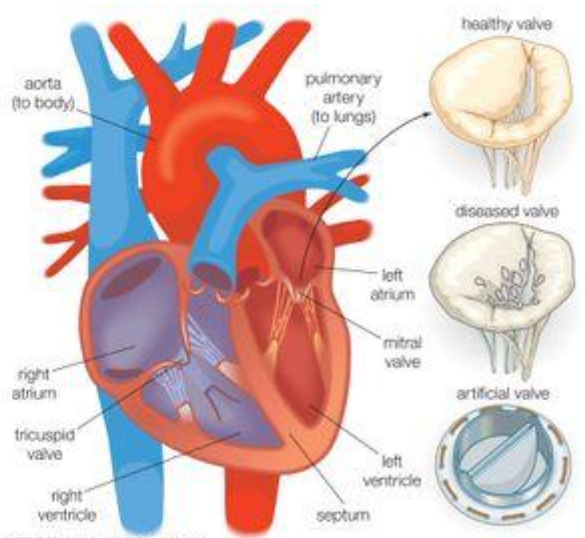
Thermosets

Thermosetting polymers find only limited application in medicine, but their characteristic properties, which combine high strength and chemical resistance, are useful for some orthopedic and dental devices. Thermosetting polymers such as epoxies and acrylics are chemically inert, and they also have high modulus and tensile properties with negligible elongation (1 to 2 percent). The polymer chains in these materials are highly cross-linked and therefore have severely restricted macromolecular mobility; this limits extension of the polymer chains under an applied load. As a result, thermosets are strong but brittle materials.

Cross-linking inhibits close packing of polymer chains, preventing formation of crystalline regions. Another consequence of extensive cross-linking is that thermosets do not undergo solid-melt transformation on heating, so that they cannot be melted or reprocessed.

Applications of biomaterials

Cardiovascular devices



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artificial heart valve Diagram showing a normal heart valve compared with an artificial heart valve.

Biomaterials are used in many blood-contacting devices. These include artificial heart valves, synthetic vascular grafts, ventricular assist devices, drug-release systems, extracorporeal systems, and a wide range of invasive treatment and diagnostic systems. An important issue in the design and selection of materials is the hemodynamic conditions in the vicinity of the device. For example, mechanical heart valve implants are intended for long-term use. Consequently, the hinge points of each valve leaflet and the materials must have excellent wear and fatigue resistance in order to open and close 80 times per minute for many years after implantation. In addition, the open valve must minimize disturbances to blood flow as blood passes from the left ventricle of the heart, through the heart valve, and into the ascending aorta of the arterial vascular system. To this end, the bileaflet valve disks of one type of implant are coated with pyrolytic carbon, which provides a relatively smooth, chemically inert surface. This is an important property, because surface roughness will cause turbulence in the blood flow, which in turn may lead to hemolysis of red cells, provide sites for adventitious bacterial adhesion and subsequent colonization, and, in areas of blood stasis, promote thrombosis and blood coagulation. The carbon-coated holding ring of this implant is covered with Dacron mesh fabric so that the surgeon can sew and fix the device to adjacent cardiac tissues. Furthermore, the porous structure of the Dacron mesh promotes tissue integration, which occurs over a period of weeks after implantation.

While the possibility of thrombosis can be minimized in blood-contacting biomaterials, it cannot be eliminated entirely. For this reason, patients who receive artificial heart valves or other blood-contacting devices also receive anticoagulation therapy. This is needed because all foreign surfaces initiate blood coagulation and platelet adhesion to some extent. Platelets are circulating cellular components of blood, two to four micrometres in size, that attach to foreign surfaces and actively participate in blood coagulation and thrombus formation. Research on new biomaterials for cardiovascular applications is largely devoted to understanding thrombus formation and to developing novel surfaces for biomaterials that will provide improved blood compatibility.

Synthetic vascular graft materials are used to patch injured or diseased areas of arteries, for replacement of whole segments of larger arteries such as the aorta, and for use as sewing cuffs (as with the heart valve mentioned above). Such materials need to be flexible to allow for the difficulties of implantation and to avoid irritating adjacent tissues; also, the internal diameter of the graft should remain constant under a wide range of flexing and bending conditions, and the modulus or compliance of the vessel should be similar to that of the natural vessel. These aims are largely achieved by crimped woven Dacron and expanded polytetrafluoroethylene (ePTFE). Crimping of Dacron in processing results in a porous vascular graft that may be bent 180° or twisted without collapsing the internal diameter.

A biomaterial used for blood vessel replacement will be in contact not only with blood but also with adjacent soft tissues. Experience with different materials has shown that tissue growth into the interstices of the biomaterials aids healing and integration of the material with host tissue after implantation. In order for the tissue, which consists mostly of collagen, to grow in the graft, the vascular graft must have an open structure with pores at least 10 micrometres in diameter. These pores allow new blood capillaries that develop during healing to grow into the graft, and the blood then provides oxygen and other nutrients for fibroblasts and other cells to survive in the biomaterial matrix. Fibroblasts synthesize the structural protein tropocollagen, which is needed in the development of new fibrous tissue as part of the healing response to a surgical wound.

Occasionally, excessive tissue growth may be observed at the anastomosis, which is where the graft is sewn to the native artery. This is referred to as internal hyperplasia and is thought to result from differences in compliance between the graft and the host vessels. In addition, in order to optimize compatibility of the biomaterial with the blood, the synthetic graft eventually should be coated with a confluent layer of host endothelial cells, but this does not occur with current materials. Therefore, most proposed modifications to existing graft materials involve potential improvements in blood compatibility.

Artificial heart valves and vascular grafts, while not ideal, have been used successfully and have saved many thousands of lives. However, the risk of thrombosis has limited the success of existing cardiovascular devices and has restricted potential application of the biomaterials to other devices. For example, there is an urgent clinical need for blood-compatible, synthetic vascular grafts of small diameter in peripheral vascular surgery—*e.g.*, in the legs—but this is currently impracticable with existing biomaterials because of the high risk of thrombotic occlusion. Similarly, progress with implantable miniature sensors, designed to measure a wide range of blood conditions continuously, has been impeded because of problems directly attributable to the failure of existing biomaterials. With such biocompatibility problems resolved, biomedical sensors would provide a very important contribution to medical diagnosis and monitoring. Considerable advances have been made in the ability to manipulate molecular architecture at the surfaces of materials by using chemisorbed or physisorbed monolayer films. Such progress in surface modification, combined with the development of nanoscale probes that permit examination at the molecular and submolecular level, provide a strong basis for optimism in the development of specialty biomaterials with improved blood compatibility.

Orthopedic devices

Joint replacements, particularly at the hip, and bone fixation devices have become very successful applications of materials in medicine. The use of pins, plates, and screws for bone fixation to aid recovery of bone fractures has become routine, with the number of annual procedures approaching five million in the United States alone. In joint replacement, typical patients are age 55 or older and suffer from debilitating rheumatoid arthritis, osteoarthritis, or osteoporosis. Orthopedic surgeries for artificial joints exceed 1.5 million each year, with actual joint replacement accounting for about half of the procedures. A major focus of research is the development of new biomaterials for artificial joints intended for younger, more active patients.

Hip-joint replacements are principally used for structural support. Consequently, they are dominated by materials that possess high strength, such as metals, tough plastics, and reinforced polymer-matrix composites. In addition, biomaterials used for orthopedic applications must have high modulus, long-term dimensional stability, high fatigue resistance, long-term biostability, excellent abrasion resistance, and biocompatibility (*i.e.,* there should be no adverse tissue response to the implanted device). Early developments in this field used readily available materials such as stainless steels, but evidence of corrosion after implantation led to their replacement by more stable materials, particularly titanium alloys, cobalt-chromium-molybdenum alloys, and carbon fibre-reinforced polymer composites. A typical modern artificial hip consists of a nitrided and highly polished cobalt-chromium ball connected to a titanium alloy stem that is inserted into the femur and cemented into place by in situ polymerization of polymethylmethacrylate. The articulating component of the joint consists of an acetabular cup made of tough, creep-resistant, ultrahigh-molecular-weight polyethylene. Abrasion at the ball-and-cup interface can lead to the production of wear particles, which in turn can lead to significant inflammatory reaction by the host. Consequently, much research on the development of hip-joint materials has been devoted to optimizing the properties of the articulating components in order to eliminate surface wear. Other modifications include porous coatings made by sintering the metal surface or coatings of wire mesh or hydroxyapatite; these promote bone growth and integration between the implant and the host, eliminating the need for an acrylic bone cement.

While the strength of the biomaterials is important, another goal is to match the mechanical properties of the implant materials with those of the bone in order to provide a uniform distribution of stresses (load sharing). If a bone is loaded insufficiently, the stress distribution will be made asymmetric, and this will lead to adaptive remodeling with cortical thinning and increased porosity of the bone. Such lessons in structure hierarchy and in the structure-property relationships of materials have been obtained from studies on biologic composite materials, and they are being translated into new classes of synthetic biomaterials. One development is carbon fibre-reinforced polymer-matrix composites. Typical matrix polymers include polysulfone and polyetheretherketones. The strength of these composites is lower than that of metals, but it more closely approximates that of bone.

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