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How Might We Help Designers Understand Systems?

Hugh Dubberly
Paul Pangaro

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HUGH DUBBERLY
Dubberly Design Office, USA
hugh@dubberly.com

PAUL PANGARO
American Society for Cybernetics, USA;
School of Architecture and School of Design,
Carnegie Mellon University, USA
ppangaro@cmu.edu

Abstract
The Future of Design Education working group on systems outlines the growth of professional practice from a focus on designing artifacts to also include designing systems and designing in the context of systems. They describe a holistic approach to design, one grounded in systems theory and recognition that systems intersect with all aspects of design. They acknowledge that systems are social constructions and can be framed in many ways. They assert that systems exhibit structural and behavioral patterns across instances, and they advocate for the development of models (proxies) that forefront these patterns and make it possible to align views of situations and possible future ways of being with teams and stakeholders under participatory design processes. The working group also notes that systems are never complete and that even small changes may have large effects. This article lists a series of recommendations aimed at design students regarding the knowledge that they should have and the actions that they should take when working around systems, and it provides an overview through which to consider more specific recommendations related to natural, social, and technical systems by other Future of Design Education working groups.

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Every day, our world seems to grow more complex. Creating better ways of being in the world, that is, designing responsibly, requires understanding systems — natural, social, and technical — and their interplay. Understanding systems is essential when intervening in ecological, economic, and political issues. Understanding systems is also increasingly necessary in designing better products and services. It frames a new approach to design practice that has been emerging for years. And it requires a corresponding shift in design education.

Wharton School of Management professor Russell Ackoff summed up a key issue, "Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other."[1] He called them "messes," and design theorist Horst Rittel called them "wicked problems."[2] A less judgmental term might be "tangles."

No matter what terms we use, most challenges-that-really-matter involve interaction among natural, social, and technical systems — for example, energy and global warming; water, food, and population; and health and social justice. And in the day-to-day world of business, new products that create high value almost all involve systems.

Part of the difficulty for the public, designers, planners, and managers is the nature of these systems. They are complex (made of many parts, richly connected) and dynamic (growing and interacting with the world). They are also hard to predict, easily disturbed, partly self-regulating or even adaptive, emergent and perhaps chaotic, and maybe unknowable. Compounding the difficulty is that the systems at the core of challenges-that-really-matter may not appear as *wholes*. Often dispersed in space, their "system-ness" is experienced primarily over time. These factors may impede finding a common frame and shared values.[3]

In many practices, designers face a shift from designing discrete artifacts to creating conditions in which dynamic systems can thrive and evolve. Designers must embrace working with *systems of systems* (information-product-service ecologies, other socio-technical systems, and nature itself). They must also embrace designing conditions for others to design; the *design of design* (meta-design, developing platforms on which others build).

These shifts in the world and in design practice require corresponding shifts in design education. Design education must move beyond focusing on objects and messages, or even interactions, to embrace systems. Regardless of the particular practice area (industrial, communications, UI/UX, service, transition, or other), the education of all design students should include core ideas and skills related to systems.

The primary purpose of the article is to describe what constitutes a system, how systems behave, and why that matters for design practice and design education. What follows are descriptions of ten concepts that are core to working with systems. (The number ten is arbitrary.) They fall into three broad groups:

1 Russell L. Ackoff, "The Future of Operational Research Is Past," *Journal of Operational Research Society* 30, no. 2 (1979): 93–104, https://doi.org/10.1057/jors.1979.22.

2 Horst W. J. Rittel and Melvin M. Webber, "Dilemmas in a General Theory of Planning," *Policy Sciences* 4, no. 2 (1973): 155–69, https://www.jstor.org/stable/4531523.

3 Hugh Dubberly, "A Systems Literacy Manifesto," October 17, 2015, http://www.dubberly.com/articles/a-systems-literacy-manifesto.html.

First, setting the context of working with systems

1 Working with systems requires a holistic approach.
2 Systems intersect with all dimensions of designing.
3 Systems theory informs multiple design perspectives.

Second, understanding systems

4 Systems are constructed.
5 Systems may be framed in many ways.
6 Systems exhibit patterns in structure and behavior.
7 Working with systems requires models.

Third, considering broader issues

8 Systems are never complete.
9 Even small changes to systems may have large effects.
10 Working with systems raises ethical issues.

The core concepts (overarching principles) and related competencies (things to know and do) may contribute to courses in systems design or be incorporated into other courses. Competencies are instrumental to taking action on the core concepts. They describe specific content knowledge and skills. They are starting points for discussion, experimentation, and learning. This article draws on courses the authors have taught at Stanford University, School for the Visual Arts, College for Creative Studies, California College of the Arts, Carnegie Mellon University, and Northeastern University over twenty years — and also on discussions with many colleagues teaching systems courses and practicing in systems design.

The main audiences for this article are faculty and administrators considering changes in design curricula. At the same time, the article may also serve design students and practitioners interested in learning more about systems and design.

It describes the following competencies in terms of what design students should *know* and *do* as they graduate from college and seek entry into the workforce; however, these recommendations have broader implications. They also apply to design professionals contemplating new kinds of work, advocating for design in their organizations, or simply trying to remain relevant in a rapidly changing professional context for which a traditional artifact-centered education did not prepare them. Managers and members of product development teams will also benefit from seeing the complexity of the modern world through a systems lens. The recommendations also apply to executives who want to position their organizations to respond strategically and responsibly to ongoing change. Furthermore, they suggest essential concepts that should inform curricula at all levels in all disciplines so that students arrive at college and work with a predisposition for systems thinking. Ultimately, incorporating systems thinking into our collaborations is the responsibility of us all.

1. Working with systems requires a holistic approach.

Working with systems requires designers to consider context, connections, and consequences; parts and wholes; stocks and flows of material, energy, and information; transformations and feedback; the sources of inputs and the disposition of outputs; larger and smaller scales; longer and shorter periods; which groups and actions are empowered or inhibited; and other dimensions of systems. Designers must also consider how a situation's natural, social, and technical aspects interact.

What design students should know:

- A *system* is a set of elements that someone sees as related in some way and that persists, often with a purpose and often with unforeseen outcomes.
- An *observer* defines a system's boundaries within an *environment*. The system may seek to maintain certain relationships with its environment, for example, maintaining dynamic equilibrium in the face of ongoing disturbances; that is, it may seek "to preserve its manner of living."[4]
- Systems range from small to large, simple to complex, tame to wicked, and few elements to huge populations. They span all domains, from aesthetics to zoology, natural systems to social and technical systems.
- The frame of systems is a way of looking at the world — searching for systems, interpreting experience in terms of interacting elements, and applying ideas from systems theory. The frame of systems crosses domains and suggests an underlying order. It provides shared language, helping people from different domains to talk with one another about patterns they see recurring.

What design students should do:

Students should take a *whole systems* approach in their work. This involves through-looping in a process of feedback and design (observe, reflect, and make — then course-correct and iterate as the situation requires). Concerns addressed in this process include:

- Parts and wholes — not just the individual artifact they are designing (for example, object, space, message, or touchpoint), but also how the artifact is enmeshed in networks of relationships. Systems designers examine the context of the artifact: the stakeholders, goals, activities, interactions, and environments that the artifact gathers together; and the stages of its lifecycle: sources (inputs), supply chains, manufacturing processes, distribution chains, consumption, disposal, and sinks (the artifact's "final" resting place). They should also consider the meaning of the artifact, what it promises, how it fits into value chains, its direct effects, and its later consequences.

- The goals-means network in which their work is enmeshed:
  - Design processes often seek *means* to fulfill *goals*. A goal at one level might be a means to a higher-level goal; for example, maintaining the temperature in the room might be a first-order goal and a means of supporting a second-order goal of comfort. A whole-system approach to designing seeks to understand networks of goals and means.
  - What goals does the project serve?
  - What are the goals above those hierarchically? And above those? (Keep moving higher.)

4 Humberto R. Maturana and Francisco J. Varela, *Autopoiesis and Cognition: The Realization of the Living*, vol. 42 of *Boston Studies in the Philosophy of Science*, ed. Robert S. Cohen and Marx W. Wartofsky (Dordrecht, NL: Reidel Publishing, 1972), https://doi.org/10.1007/978-94-009-8947-4.

5 **Stewart Brand, *The Clock of the Long Now: Time and Responsibility* (New York: Basic Books, 1999), 37. Especially see Figures 4 and 5 in Meredith Davis and Hugh Dubberly, "Rethinking Design Education," *She Ji: The Journal of Design, Economics, and Innovation* 9, no. 2 (2023): 97–116, https://doi.org/10.1016/j.sheji.2023.04.003.**

  - What does the project make possible? What opportunity space does it open up?
  - What effects does it enable? And below those? (Keep moving lower.)
  - What alternatives might be considered at each level?

- The situation at multiple scales. For example, a house sits in a block or neighborhood, nested in a district, in a region, in a state, and so on. At the same time, the house contains rooms; the rooms contain doors, windows, and furniture; these, in turn, contain subcomponents such as handles, frames, or cushions—any of which may contain their own components, and so on. Looking beyond the immediate focus of a project to the next larger and smaller scale (or two), may yield insights. In addition to physical size, the scale of a system may also refer to the number of constituents, the variety of constituents, the complexity of relations between constituents, the number of stakeholders or people affected by the system, and other factors.

- Multiple time frames.
  - Where does the project fit within futurist Stewart Brand's pace-layer model?[5] What is the main pace-of-change—fast or slow or in-between? How does the project relate to adjacent systems or layers that might change at faster and slower paces?
  - What are the natural rhythms of using the artifact, service, or system? Where does it change quickly? Where does it change slowly?
  - What aspects of the system (and its related social systems) help it to adapt to a rapidly changing world? What aspects help it to conserve its essential properties over time?
  - What effects will the project have over weeks, months, years, lives, and generations?

2. Systems intersect with all dimensions of designing.

Systems theory provides *frames* for observing the world and making sense of it—frames for understanding. Systems theory also helps designers understand: what is designed (framing "the system" to be a result of a design process); potential consequences or effects on other systems and the mitigation of actual consequences; the context of use for what is designed; and the design processes itself.

What design students should know:

- **Production systems**—Descriptions of the origins of design sometimes distinguish between design in the context of craft making and design in the context of mass production. In this idealized story, pre-industrial craft makers custom-fitted artifacts for use in a specific place. The craft maker knew the intended user and surroundings well. Designing was tightly integrated with making and informed the whole process. The rise of the Industrial Revolution separated designers from makers; they lost touch with users, and designing became a separate planning phase

6 Christopher Alexander, *Notes on the Synthesis of Form* (1964; Cambridge, MA: Harvard University Press, 2000), 73–76.

preceding mass production.[6] The making of artifacts shifted from an ad hoc, one-off process to a tightly controlled, repeatable production system. These systems of production themselves required designing and benefitted from improvements made through iteration. Increasingly, production systems are becoming digital, with one result being that mass production can now be mass customization, tailoring products to the individual's needs once again. For example, database-driven ink-jet printing enabled a journal to publish a unique photo of each subscriber's house on the cover; likewise, jeans, sneakers, and even cars can be custom manufactured.

- **Design systems**—Often, artifacts need to relate to other artifacts—that is, they need to fit or otherwise work together in a system. A design system makes this possible and itself requires design and benefits from iteration. Design systems manage design at scale. They support theme and variation, enabling flexibility while maintaining coherence. Design systems function by providing:
  - A collection of reusable components (kits of parts, toolkits, and libraries).
  - Rules for their use (templates, error-checkers, and APIs—application programming interfaces).
  - Procedures for extending the system (systems of governance).

A classic example of a design system is a subway signage system. Subways (systems in their own right) change; they add, modify, and sometimes eliminate stations, routes, timetables, equipment, and more. Replacing all the signage every time the subway adds a station makes little sense. Instead, what is needed is a design system that can adapt—a system that anticipates future change (or at least some reasonable types of change). Other examples of design systems include building systems, clothing systems, dinnerware systems, exhibit systems, furniture systems, grid systems, identity systems, office systems, packaging systems, software libraries, and typefaces.

Design systems provide templates, patterns, or platforms that others can use to design new instances in the spirit of the original system. Thus, designing design systems is a type of *meta-design*, the design of the means or situations in which other people, or perhaps even algorithms, can design.

Designers interact with design systems at six levels:

- Acting outside the system.
- Accepting and applying the system.
- Extending the system.
- Managing the system.
- Creating the system. (Or later transforming it.)
- Automating the system.

Much of the work designers do is still "one-off" and falls outside any design system. However, design systems increasingly govern the work of most designers. The designer often follows the design system's rules, using existing elements to create new artifacts *within* the system. Thus, they maintain a consistent formal style, structure, and behavior patterns that set user expectations and make learning, use, and development more efficient. More experienced designers may recognize new situations not anticipated by the original system designers. These situations may require modifying or extending system components, rules, or both. A further level of expertise involves managing the operation of an existing design system — that is, overseeing its use by less experienced designers and developers, resolving issues, and ensuring the success of extensions. Organizations may call on experienced designers to create a new design system for other designers to use or to create a new product system that non-designers can configure.

Sometimes, updating or otherwise "transitioning" to a new system requires even more experience than creating a new system from scratch. This is because considerable additional effort is involved in gaining consensus across an organization and managing the transition without disrupting ongoing operations.

Creating and managing a design system involves a range of social and technical systems. For example, modern software companies deploy various technical platforms for bug tracking, content management, project management, and version control. Systems automate the review of submissions and test them against standards (for example, quality assurance systems). They also document rationales for decisions and manage change processes and design debt (unfinished work, known issues or bugs, and suggestions for improving the experiences of users; these elements are often deferred in favor of a quick product release). Large organizations also develop systems of governance for managing changes to the design system. Emerging best practices at firms like Intuit integrate the governance of design systems and software code libraries. Internal stakeholder-led committees run formalized change-management processes — identifying issues, proposing revisions to design systems and code libraries, gaining consensus, and implementing decisions — while involving feedback from designers, developers, managers, and customers.

- **Design *for* systems** — Often, design systems are nested. For example, a designer might design a symbol (like the letter "S") that is part of a system of letters (an alphabet). That alphabet might be part of a typeface, itself a part of a typeface family. A typeface from one character set might be extended to other character sets (from Roman to Greek, Cyrillic, Arabic, Hebrew, and the rest of the world's scripts). In addition, this universal font family might include variations in weight, proportion, and posture. It might support all languages. Furthermore, this font family may be the cornerstone of a corporate identity system, itself instantiated in a complex technical system. The technical system nests a template system (with fonts and styles) in a publishing system (for posting to the web or sending email), further nested within a content management system (CMS). The content management system is tied to a customer relationship management system (CRMS) and marries marketing content with names, addresses, and other information about potential customers. These technical systems support marketing and sales programs (systems), bringing in revenue that maintains a larger organization, itself a system tied to many stakeholders (also systems).

Across that process, design systems overlap other socio-technical and natural systems. In the past, designers might have drawn the letter with a pen or brush, carved it in stone, or cast it in metal. Today, they are likely to outline the letter on a computer, relying on a complex stack of systems—for example, microprocessor, operating system (with embedded font rendering), browser (with embedded page rendering), application, and page-description language (such as PostScript). These systems rely on a series of communication protocols (the internet) and server computing protocols (the edge or cloud). Each layer of these stacks requires ongoing design, management, and iteration.

Increasingly, products that once stood on their own are tied to the internet, edge networks, and cloud computing in smart-connected product systems, systems of systems, or information-product-service ecologies. The design of these systems is the emerging domain of design practice. Practitioners in this new domain will benefit from an understanding of systems theory.

What design students should do:

- Investigate as much as they can about the systems of production across the design specializations in which they work.
- Study classic design systems—their elements, rules, and governance—and how they were embodied, shared, and deployed. Identify the basics of permutation and combination (programmatically exploring variations within a given space of possibilities and systematically merging sub-sets of elements from a larger super-set). In addition, they should also explore the differences between theme and variation, type and token, class and instance—to better understand how designers, writers, and musicians (and even nature) achieve unity in variety.
- Become familiar with today's leading design systems, such as Google's Material Design system. Use modern tools for managing design systems and best practices for governing design systems and software libraries.
- Question existing design systems from relevant perspectives, such as fit-to-context (the general situation); fit-to-purpose (the process, configuration, and service that is capable of meeting specific objectives); trade-offs between coherence and responsiveness; robustness and flexibility; scale and ease of use; and infrastructure for management and governance.
- Design information-product-service ecologies. Many designers are eager to design apps for smartphones, not recognizing that the industry is moving beyond apps. Rather than stand-alone apps, designers should consider a series of touchpoints across a service journey. For example, a person with diabetes might wear a continuous glucose monitor (CGM) that "talks" to an insulin pump. Both the monitor and pump may talk to a smartphone that runs a related app. In addition, the phone app talks to a database in the cloud, which provides information to designated family members and healthcare providers (HCPs). In such a context, designers might map how insulin and blood glucose interact (information

7 Peter Kropotkin, *Mutual Aid: A Factor in Evolution* (New York: McClure Phillips & Co., 1902).

8 James Clerk Maxwell, "On Governors," *Proceedings of the Royal Society of London* 16 (December 1868): 270–83, https://doi.org/10.1098/rspl.1867.0055.

9 Claude E. Shannon, "A Mathematical Theory of Communication," *The Bell System Technical Journal* 27, no. 3 (1948): 379–423, 623–56, https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

10 Norbert Wiener, *Cybernetics: Or Control and Communication in the Animal and the Machine* (1948; Cambridge, MA: MIT Press, 1961).

controlling stocks and flows). They might map people and care networks, disease progression and patient journeys, and technical systems and their interactions. Further steps might look at interactions with ambient displays (for example, flagging a critical condition), systems involved in clinical trials, or systems that collect and fuse data from other sources.

- Work within an existing design system, applying existing system rules to known cases (and critiquing the work of fellow designers to understand what constitutes following the rules). Then, extend the system by finding cases it does not cover. Type designer Matthew Carter, for example, did this with a brilliant but simple problem: to design old-style figures for use in Helvetica text. A more current assignment would be to create a set of nested design libraries in Figma—for example, style libraries for Brand A and Brand B, a component library, screen instances for a simple mobile app, and culminating with automated switching of the brand assets. While there is immediate commercial value in being able to use Figma at that level, the long-term value for designers is in developing experience with modular design and intuition about how to organize design systems.

3. Systems theory informs multiple design perspectives.

Three distinct perspectives are of particular interest. Many designers are familiar with systems as *management tools*. For example, grids help designers manage large sets of diverse information, contributing to *design programs*. Likewise, design systems themselves are tools for managing suites of products and teams of people. Increasingly, designers understand systems as an aspect of sustainability and related topics—for example, the circular economy. And more recently still, designers see systems as a *material* with which they design. For example, service systems and information systems are central components of the new economy; information-product-service ecologies, like Amazon, and the subsequent digital transformation affect all aspects of everyone's lives. Systems theory is a body of knowledge applicable to the above perspectives. Within systems theory are several schools of thought or historical clusters of people and ideas.

What design students should know:

- **The major branches of systems theory**—Systems theory has a long history going back to inventor James Watt and the beginning of the Industrial Revolution. The first academic writing in the field appeared in the mid-nineteenth century with Mendel, Darwin, and others, followed in the twentieth century by Kropotkin[7] and Watson-Crick-Franklin et al. Another thread begins with Maxwell in 1868,[8] followed by Shannon[9] and Wiener[10]—both in 1948—and others since then. Several schools of thought have emerged around systems theory. Each has its own history and canon (too long to list here), and they all have applications to design:
  - General systems theory.
  - Systems dynamics (for example, stocks and flows).
  - Information theory and feedback (components of cybernetics).
  - Network science.

- Theories of evolution, interaction, conversation, and learning.
- Complexity, chaos, and catastrophe theories (for example, the study of emergent behaviors and self-organization).
- Game theory and voting systems.

- **The major categories of systems**—For simplicity's sake, the Future of Design Education project has divided systems into three (nested) categories: *Natural systems* (for example, genes, cells, plants, animals, and ecologies) support and are affected by *social systems* (for example, groups, organizations, communities, and languages), which support and are affected by *technical systems* (for example, products, buildings, services, and platforms).
  - This special issue discusses natural systems in the article on sustainable design;
  - Social systems, in the article on the pluriverse;[11] and
  - Technical systems, in the article on information technology and the use of data.

  Of course, other taxonomies are also worth considering, and the other Future of Design Education articles only begin to tell the story of these branches; they do not purport to be complete. In practice, these boundaries are fuzzy. For example, the design of a classic smart-connected product like the Nest thermostat touches on all three branches of systems.

- **Generative systems** — Another perspective on systems is their role in automating and augmenting design. Already, algorithms can "be trained on" a body of work (for example, paintings or musical compositions by a particular artist) and produce similar works in the style of the originals. The next generation of designers may find much of their work to be "training" such systems and creating rule sets that machines will use to generate large numbers of variations, particularly for structural and formal configurations of elements. Then, designers or product management teams will evaluate the resulting options. A further step is for designers to add rules-for-selection to systems with rules-for-variation. These systems (of variation and selection) are sometimes known as genetic algorithms. They aid designers and product teams in considering more options more quickly—so teams can iterate faster, improving quality while also increasing efficiency.

  Early generative design systems tended to focus on form or structure. MIT Media Lab co-founder Nicholas Negroponte and others have imagined higher-level systems that engage in conversations with designers and help them formulate goals. For example, Negroponte imagined "an architecture machine" working alongside human architects.[12] However, such systems are currently more aspirational than reality, though ChatGPT and "prompt engineering" begin a dialog between designers and algorithms.

What design students should do:

- Read broadly in the literature of systems theory. Learn its history and how concepts developed.

11 Arturo Escobar, *Designs for the Pluriverse: Radical Interdependence, Autonomy, and the Making of Worlds* (Durham, NC: Duke University Press, 2018).

12 Nicholas Negroponte, *The Architecture Machine: Toward a More Human Environment* (Cambridge, MA: MIT Press, 1973).

- Find and apply today's generative design tools. Play with them. Apply them to the design process. For example, explore cellular automata (a collection of filled or unfilled cells on a grid that evolve through discrete steps according to a set of rules based on the states of neighboring cells). An example is John Conway's "Game of Life."[13] Keep up with developments in low-code/no-code software and generative AI systems, such as DALL-E and GPT.
- Explore related topics such as solution spaces, optimization techniques (for example, hill climbing with gradient descent), linear integer programming, simulated annealing, recursion, fractals, and genetic algorithms.
- "Take your pleasure seriously," said Charles Eames. Designers and students should enjoy their work, delight in what they do, have fun, and even make a game of it. Graphic designer Paul Rand pointed out that the best teachers appeal to a student's play instinct. Playing with design systems, neural nets, and large language models (LLMs) may be the best way to understand them. "Messing about" and "hacking" are time-honored ways to learn code. Likewise, with systems, designers and students should poke at them, tinker, and see what happens. They should live with them and get the feel of them. While these skills may at first seem difficult to measure, curious students are easy to spot. By providing opportunities for play, faculty may encourage greater curiosity.

4. Systems are constructed.

People draw boundaries; they decide what to include and what to leave out, resulting in the continuous negotiation of systems as people discuss them and decide which distinctions matter. In other words, systems are political. Everyone brings their own frame, which limits what they are able to see. Observers are always part of the picture; no "outside" view exists. Moreover, observers may also affect what they observe.

What design students should know:

- Design is subjective, rhetorical, and political.[14] Artifacts and technologies have politics.[15] Likewise, social processes and the categories into which people sort things also have politics.[16] In short, socio-technical systems (STS) are inherently political, as are the relationships between socio-technical systems and natural systems.
- A conceit of science is that observers may stand outside a system looking in and that substituting one observer for another will not change what they report seeing. In design situations, where participants seek to intervene in the system, an objective view is impossible. Designers are deeply enmeshed in the situation and bring their own experiences, values, and concerns. They cannot stand outside the situation and merely observe. Participation makes them responsible.[17]
- People's perception of the complexity of a system is tied to how they frame and understand it. In other words, it depends on the language they develop to explain it.[18] For example, the flocking behavior of birds manifests in myriad forms; yet a few simple rules are enough to create a life-like simulation. Likewise, complex shapes such as trees and clouds are difficult to

13 Martin Gardner, "Mathematical Games: The Fantastic Combinations of John Conway's New Solitaire Game 'Life,'" *Scientific American* 223, no. 4 (1970): 120–23, https://www.jstor.org/stable/24927642; see also John Conway, *The Game of Life*, accessed June 19, 2023, https://playgameoflife.com/.

14 Horst W. J. Rittel, "On the Planning Crisis: Systems Analysis of the 'First and Second Generations,'" *Bedrifts Økonomen* 8 (1972): 390–96; Richard Buchanan, "Declaration by Design: Rhetoric, Argument, and Demonstration in Design Practice," *Design Issues* 2, no. 1 (1985): 4–22, https://doi.org/10.2307/1511524.

15 Langdon Winner, "Do Artifacts Have Politics?" *Daedalus* 109, no. 1 (1980): 121–36, https://www.jstor.org/stable/20024652.

16 Lucy Suchman, "Do Categories Have Politics? The Language/Action Perspective Reconsidered," in *Proceedings of the Third European Conference on Computer-Supported Cooperative Work*, ed. G. de Michelis, C. Simone, and K. Schmidt (Dordrecht, NL: Springer, 1993), 177–90, https://doi.org/10.1007/978-94-011-2094-4_1.

17 See writing by Gregory Bateson, Humberto Maturana, and Heinz von Foerster.

18 Heinz von Foerster, "The Curious Behavior of Complex Systems: Lessons from Biology," *Special Collections: Oregon Public Speakers,* February 28, 1975, available at https://pdxscholar.library.pdx.edu/orspeakers/125.

describe with Euclidian geometry but easy to describe with recursion and fractal geometry.

What design students should do:

- Critically evaluate definitions and assumptions. Make them explicit, share them, invite discussion, and iterate.

- Ask themselves, colleagues, and other stakeholders:
  - Where is the boundary between the system and the environment?
  - What is inside the system? (Its parts or constituent elements)
  - How do the parts of the system affect each other? (Their relationships)
  - What is outside the system? What does it affect? What disturbs it?
  - How do the system and the environment interact?
  - What crosses the boundary between them? (For example, stocks, energy, and information)
  - What patterns of structure and behavior repeat?
  - What relationships does the system conserve?
  - How does the system's behavior differ from that of its parts? What emerges?

- Describe and account for the context of the design process:
  - Who frames the situation? Who gains or loses? What and how?
  - Who determined the boundary?
  - Why did they put it where they put it?
  - What are their goals? (Especially in setting the boundary)
  - What are the alternatives? Where might other boundaries be drawn?

5. Systems may be framed in many ways.

Systems may be framed in as many ways as there are situations and observers. The best approach to framing a system depends primarily on the observer's goals. In design situations, the stakeholders' goals should take precedence along with considerations about the system type and context.

Systems may be viewed in terms of:

- Their parts (form and constituent elements).
- Their materials (natural, social, and technical).
- Their structure (the relationships between their parts).
- Their growth (how they form and evolve).
- Their purpose (goals—the relationships they seek to maintain).
- The people involved (participants, stakeholders, designers, and other "observers").

Building on that foundation, systems may also be understood as:

- Sets of relationships that affect each other.
- Stuff that flows through a process (for example, physical stocks).
- Energy flowing in (briefly concentrated) and flowing out (always dissipating).

- Information exchanged between actors.
- Internal variety that counters disturbances from external variety.
- Configurations that can re-make themselves (applies to some but not all systems).

What design students should know:

- Just as design questions have no "right" answers, there is no right way to describe an existing system (for example, describing what is otherwise unnoticed or unexpressed, enabling communication of complex concepts and relationships, or offering artifacts as the basis for collaboration). Likewise, there is no right way to organize a new system; however, some configurations may be more effective or efficient in meeting their goals or more robust in maintaining themselves than others.

What designers should do:

- Study specific systems in depth. Take them apart and put them back together again. Identify and map their components and relationships. Analyze them under as many different frames as possible. Pay special attention to how systems interact with other systems — how technical systems affect social systems and how social systems (or socio-technical systems) affect natural systems and vice versa.
- Study a type of system, looking for many variations of the type. For example, compare and contrast types of thermostats: mechanical switches, programmable thermostats, learning thermostats, smart thermostats, and communicating (bi-directional) thermostats. Look for and map the dimensions of the solution space. Look for and map systems that are similar in function and structure. And look for and map similar patterns of behavior. For example, thermostats and insulin management systems have similar structures and behaviors. Comparing and contrasting system maps side-by-side may improve understanding of both the type of systems and the specific instances.
- Study the context (the larger systems in which the system type is embedded). Look for and map relationships between super-ordinate and sub-ordinate systems. Describe variations in the solution space at different scales. For example, thermostats can control many types of heating and cooling systems, which are parts of "smart" home management systems and larger power-generating systems. These nested systems influence decisions about managing the grid and safety, regulating the industry, and making a profit.

6. Systems exhibit patterns in structure and behavior.

In systems, basic patterns repeat across instances and across domains. Working from instance to pattern and back helps designers better understand the particular systems they encounter. The lists below constitute the vocabulary of systems thinking — the core content designers should learn for working with systems.

What design students should know:

- **Information structures—**
  - The primary structures (or *primitives*): name-value pairs, arrays, trees, matrices, and webs (networks or graphs).
  - How they can be mapped to one another.
  - Transform functions; that is, representations of how inputs affect outputs. Are they positively correlated, as in A seems to cause B? Or are they inversely related (for example, increasing interest rates tends to decrease consumer and business spending)? Most process steps can be represented in terms of their transform functions. Causal-loop diagrams (CLDs) represent transform functions using the shorthand + or –. Adobe Photoshop's Curves feature illustrates the transform function.
  - Network topologies, such as point-to-point, daisy chain, bus, ring, star, and mesh.
  - Database architectures, such as flat file, hierarchical, relational, and NoSQL (non-structured query language).

- **Shannon's Model of Communication—**
  - The process of sending a message through a channel to a receiver.
  - Encoding and decoding, which requires a shared code.
  - Signal versus noise.
  - Definition of information as the measure of the decrease in uncertainty for a receiver.
  - The modern Operating Systems Interconnection (OSI, seven-layer) network communications model.

- **Basic terminology of system dynamics—**
  - Stocks and flows, sources and sinks, and lag.
  - Re-enforcing systems, positive feedback, or "more leads to more," also called virtuous or vicious cycles. (Increasing oscillation, explosion, or collapse.)
  - Balancing systems, negative feedback, or "more leads to less."
  - Stability, dynamic equilibrium, or homeostasis.
  - Maintaining the level of a stock amid changing conditions.

- **Basic terminology of feedback control—**
  - System, environment, goal, and disturbance.
  - Sensor, comparator, actuator, and significant variable.
  - Range, frequency, and resolution (in measuring and acting).
  - Feedback, using the output of a process as information input to the process.
  - Incorporating feedback at multiple levels or *orders*.
  - Feed-forward, using leading indicators to *anticipate* upcoming disturbances.

- **Quality management or bootstrapping—**
  - The underlying process or primary transformation, for example, an assembly line.

- The first-order process of control, or quality assurance (QA) for the underlying process, for example, feedback on defects.
- The second-order (local) process for improving control (that is, learning), for example, introducing weekly quality circle meetings for workers on this line.
- The third-order (global) process for improving the process of improving control (that is, building a learning organization, one that improves how it learns), for example, having managers from across all divisions regularly share new quality improvement methods.

• **Requisite variety—**
  - Requisite variety is the information and behaviors a system requires to counter the information and behaviors brought to bear in likely disturbances.[19] It has major implications both for what is designed and also for the design process itself. Designers need to account both for likely disturbances to the systems they design and also for the variety needed on the design team. Individuals, teams, organizations, and cultures (social systems) all have variety. Likewise, technical and natural systems have variety. Determining how much variety they require (or what ranges of disturbances to anticipate) is a management challenge.

• **Redundancy of potential command—**
  - Decisions arise from valid information that may emerge from more than one source. The act of *command* is more appropriately attributed to the information that triggers the decision than to specific individuals. For example, a leader sends a scout to check if a situation is safe. When the scout signals back to the leader, "All clear!", the leader then gives the order for everyone to follow the scout. The decision arises from the information from the scout, not the act of the leader giving the order.

• **Pace layer model—**
  - Systems (particularly complex systems) may be organized into layers that operate at different paces or speeds. Layers that operate quickly may be important in responding to change. Layers that operate slowly may be important in conserving the system's structure and manner of living (including its intentions, strategies, and values).

• **Bio-cost and bio-gain—**
  - Bio-cost is the energy, attention, and stress expended over time to achieve a goal. Bio-gain comes from replenishing physical, mental, and emotional energy—for example, through eating, sleeping, and exercising. It may also come from work when one "gets in the zone," from developing a sense of meaning and purpose, or from interacting and having generative conversations with others.[20]

• **Emergent behavior—**
  - The appearance of some new *whole* that is more complex than its constituent parts.

19 W. Ross Ashby, "Requisite Variety and Its Implications for the Control of Complex Systems," *Cybernetics* 1, no. 2 (1958): 83–99, available at http://pcp.vub.ac.be/books/AshbyReqVar.pdf.

20 Hugh Dubberly, C. J. Maupin, and Paul Pangaro, "Bio-Cost: The Economic of Human Behavior," *Cybernetics and Human Knowing* 16, no. 3-4 (2009): 187–94, available at https://www.dubberly.com/articles/bio-cost.html.

21 Gordon Pask as described in Hugh Dubberly and Paul Pangaro, "What Is Conversation, and How Can We Design for It?," *Interactions* 16, no. 4 (2009): 22–28, https://doi.org/10.1145/1551986.1551991.

- **Concept of self-organization or autopoiesis—**
  - The ability of a system to reproduce and maintain itself by making its own constituent parts. See also *allopoiesis* (that is, the ability of the system to produce something other than itself, like an assembly line making products but not reproducing itself), and *dissipative systems* (which develop patterns, structures, or behaviors they did not have when first formed, like a whirlwind).

- **Process of co-evolution—**
  - The process by which systems and their environment mutually adapt. Evolution involves variation and selection (through both competition and cooperation), as well as drift (random fluctuations) and flow (recombination).

- **Pask's Model of Conversation—**
  - Interaction between two or more learning systems; it involves agreement on distinctions (understanding or constructing knowledge).[21]

What design students should do:

- Explain the basic patterns of systems.
- Identify the applicable patterns when confronted with example systems. Map elements from general patterns to elements in the specific examples.
- Having recognized a few elements from a general pattern in a specific example, identify and describe elements from the pattern not immediately visible in the example. That might mean when hearing a manager talk about goals, the designer should consider what actions will meet the goals (the means or plans), what is measured, and what the feedback cycle will be.
- Apply recognized patterns to identify actual or potential bugs, breakdowns, or inefficiencies. Apply the understanding of patterns to finding opportunities and suggesting improvements.
- Apply systems patterns from one domain to another.

7. Working with systems requires models.

When designers work with systems, they almost always participate in multi-disciplinary teams. And some project teams may include tens or even hundreds of members. Effective work requires developing shared understanding. One challenge to understanding systems is that they are often invisible or inchoate, or they may be difficult to see all at once as they stretch across space and time. Many change continuously. That means working directly on systems is not always possible; sometimes proxies are needed (including models, white-board sketches, maps, prototypes, digital twins or data-driven dynamic models). Sharing and iterating models can help teams agree on purpose, current structures, operations, bugs, goals, plans, etc. Shared models create shared understanding and alignment.

What students should know:

- What a model is, how to make one, and how to evaluate it.
- What the basic systems frameworks look like in model form (the various ways they may be diagrammed or mapped).
- All models are wrong, but some are useful.[22] Also, models improve with iteration and through discussions with stakeholders.
- The concepts of boundary objects[23] and alignment diagrams[24] illustrate how to use models with colleagues, teams, and organizations in understanding situations, imagining options, and building consensus.

What design students should do:

- Make concept maps.[25]
- Apply concept mapping techniques to process mapping.
- Make causal loop diagrams (CLDs).[26]
- Make user conceptual models and visualize them in the form of concept maps.[27]
- Make goals-means tree diagrams or goals-means network diagrams, as applicable.
- Make state diagrams.
- Make string diagrams.
- Map known systems to build skills and confidence in mapping unfamiliar systems.
- Evaluate systems against principles, stakeholder goals, viability, and responsibility to other systems. Prototype and test interventions through modeling, simulations, and pilots.
- Stay abreast of how large language models can generate diagrams.

8. Systems are never complete.

Most systems have a living quality. Much like wild places, gardens, or farms, they change continuously in response to internal and external forces. Designers will not be able to anticipate all possible disturbances in advance. That means they must set up conditions in which the system will thrive on its own without continuous outside intervention.

What design students should know:

- Designers may try to control systems, but control can be an illusion, especially as systems become larger and more complex and as disturbances become less predictable.
- The mindset of a steward or facilitator is often more appropriate for working with systems than the mindset of a problem solver or expert.
- Things can always be improved. The only stopping conditions for designing are external to the situation—conditions such as running out of time, money, or interest.[28]

What design students should do:

- Take an agile approach to systems. Try little things and see what happens. Adjust quickly. Plan for being "in beta" for a long time or indefinitely.

22 George E. P. Box, Alberto Luceño, and Maria del Carmen Paniagua-Quinones, *Statistical Control by Monitoring and Adjustment*, 2nd ed. (New York: Wiley, 2009), 61.

23 Susan Leigh Star and James R. Griesemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39," *Social Studies of Science* 19, no. 3 (1989): 389, https://www.jstor.org/stable/285080.

24 James Kalbach and Paul Kahn, "Locating Value with Alignment Diagrams," *Parsons Journal for Information Mapping* 3, no. 2 (2011): article no. 3, http://www.piim.newschool.edu/journal/issues/2011/02/pdfs/ParsonsJournalForInformationMapping_Kalbach-James+Kahn-Paul.pdf.

25 John D. Novak and D. Bob Gowin, *Learning How to Learn* (Cambridge: Cambridge University Press, 1984).

26 Donella Meadows, *Thinking in Systems: A Primer* (White River Junction, VT: Chelsea Green Publishing, 2008).

27 Jeff Johnson and Austin Henderson, "Conceptual Models: Begin by Designing What to Design," *Interactions* 9, no. 1 (2002): 25–32, https://doi.org/10.1145/503355.503366; Daniel Rosenberg, *UX Magic* (Interaction Design Foundation, 2020).

28 Rittel, "On the Planning Crisis," 392.

29 Meadows, *Thinking in Systems*.
30 Humberto Maturana, "MetaDesign," *TechnoMorphica V2*, 1997, accessed June 17, 2023, https://philpapers.org/rec/MATM.
31 Heinz von Foerster, "Ethics and Second-Order Cybernetics," in *Understanding Understanding: Essays on Cybernetics and Cognition* (New York: Springer-Verlag, 1991), 295, https://doi.org/10.1007/0-387-21722-3_14.

9. Even small changes to systems may have large effects.

The consequences of changing a system are not always apparent ahead of time. Designers and organizations must proceed mindfully and incrementally; try to leave time for adjustment and iteration. Sometimes the best choice may be to do nothing, to let the muddy pond settle. However, if a large system is unjust, delaying change is also unjust, even if the designer or organization cannot foresee all consequences.

What design students should know:
- Leverage points are places in complex systems where small changes may have big effects.[29]
- How things are measured (for example, how transducers and digital sensors work).
- How devices and scales used in measuring affect what-is-measured and the types of results reported.
- How measurements (data) become models, how models make predictions, and how predictions affect decisions—the risk that seemingly reasonable steps can lead to unfortunate outcomes.

What design students should do:
- Study leverage point frameworks. Identify illustrative examples and use them as a library of possibilities when seeking to change systems.
- With real systems, proceed slowly, scale gradually, and act humbly, particularly when the possible effects are not well-understood (when there are few precedents). Moving fast and breaking things may be catastrophic.

10. Working with systems raises ethical issues.

If design is political and key decisions reflect values, then ethics must always concern designers. This idea applies to designing systems. Many authors who have written about systems—Gregory Bateson, Heinz von Foerster, Humberto Maturana, and Norbert Wiener—have addressed ethics. Designers may benefit from reading their texts.

What design students should know:
- Everyone has a choice in their actions and is responsible for what they do.
- Designers are responsible for their choices, including the language they use, which brings forth the world in which we live together.[30]
- When other people are affected, designers are also responsible for making their choices clear, as well as for sharing their rationale for those choices.
- The choice of scales used to measure things is arbitrary. There are ethical implications in who decides what to measure and when. These issues may be functional or structural, but they can also be political and relate to who has control—who makes decisions and who is excluded.

What design students should do:
- Always try to act so as to increase the total number of choices available to others.[31]

- Distribute decision-making and minimize regulation while also ensuring a stable environment.
- Prefer augmenting (supporting human agency) over automating (giving agency to devices).
- When faced with either/or, look for both/and (for example, keyboard + mouse).
- When faced with a trade-off between coherence and responsiveness (that is, between structure and flexibility), seek to "move the curve" to get more of both.[32]

The ten key concepts outlined above provide a basis for understanding systems design. Evidence that students and young designers have internalized the concepts and understand systems manifests in their attitude, tone, and confidence in explaining issues. More concretely, young designers' representations of aspects of systems in models, diagrams, process flow maps, network structures, and other visualizations provide evidence of their understandings. However, the true indicator of learning and mastery is when designers begin to use the language of systems on their own—as a natural part of their discourse—when talking with one another and explaining their thinking to others. For example, an important milestone is when a designer naturally jumps to a whiteboard to sketch a system, in the middle of a meeting.

Bringing Systems Theory to Design Practice and Education

An understanding of systems theory benefits all types of design. It is a necessity for any design work that involves systems. And it is simply unavoidable for work involving information-product-service ecologies.

Systems design is not new. Humans have lived in and through natural, social, and technical systems for millennia. People have designed, made, and used feedback systems for over three thousand years. But in the last 150 years or so, socio-technical systems have achieved new levels of complexity and become pervasive. At the same time, our understanding of large natural ecosystems and individual biological systems has expanded greatly.

About 75 years ago, economist Friedrich Hayek,[33] engineer and mathematician Claude Shannon, and many others reframed the world in terms of information. Our culture has long been concerned with material and its form. With the Industrial Revolution, society became more concerned with motion, with power that drove motion, and with the energy that created power. The necessities of designing and managing industrial-age machines (for example, the steam engine) gave rise to early theories about systems.

Mathematician and cybernetician Norbert Wiener and many others involved in the cybernetics movement (the study of systems that use feedback to act effectively) revealed the role of information in regulating systems and creating stability (at least within constraints). They provided an answer to the question, "How does entropy always increase, yet all around us things are growing (order is increasing, at least locally)?" They supplied a vocabulary

32 Jared Harris and Austin Henderson, "Coherence and Responsiveness," *Interactions* 19, no. 5 (2012): 67–71, https://doi.org/10.1145/2334184.2334199.

33 Friedrich A. Hayek, "The Use of Knowledge in Society," *The American Economic Review* 35, no. 4 (1945): 519–30, https://www.jstor.org/stable/1809376. That Hayek precedes Shannon and Wiener by 3 years deserves acknowledgement, despite the unfortunate uses to which some have put his work.

and models for sharing ideas across disciplinary boundaries. They also laid a foundation for asking, "How might information enable people to achieve their goals?" and "How might people evolve new goals?"

The rise of the cybernetics movement helped create an environment favorable to the emergence of the design methods movement a few years later (passed on and rebranded today as design thinking). An important cradle of the design methods movement was the faculty of HfG Ulm (1953–1968). The school introduced both systems theory (for example, courses on cybernetics) and courses focused on design systems. A high watermark of this period was Swiss designer Karl Gerstner's classic book, *Designing Programmes.* Gerstner used programmes as a synonym for modular systems, or design systems.

About the same time, design of design systems took off in Europe and North America. Master planning hospital, airport, and subway signage systems became a common practice. New logos and typefaces appeared along with detailed standards manuals describing guidelines for applying them in a variety of situations. Meta-design (designing situations in which others design) emerged as a concept in design discourse.

These events took place just as computers made their way into business management. Designers began to ask, "How might computers augment designing?" The role of computers in design evolved quickly. At first, they served merely as production tools, speeding traditional design. Then computer networks became a new communication medium that needed new types of designers. And now, computing is the material out of which designers are fashioning a new world. Data and algorithms have become the wood and metal of a new generation.

This information revolution has been remarkably fast. And it is far from over. At most, it may be at the end of the beginning. But already new sociotechnical systems have fundamentally changed our economy, and even more deeply, how people communicate, interact, and govern themselves.

Systems theory is a critical tool for understanding and grappling with these changes. Designing without understanding systems raises ethical questions and might verge on malpractice. Hayek, Shannon, and Wiener pointed the way by providing information as a frame. HfG Ulm offered an alternative to the industrial frame of the Bauhaus School. The new revolution in data and algorithms makes systems theory a necessary foundation for design practice going forward. Designing and managing information-age systems makes the need to incorporate systems theory in college-level design education both clear and pressing. Basic systems literacy in general education is also essential from kindergarten through high school.

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