FINANCIAL SYSTEM ENGINEERING

MANUEL A. UTSET*

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* William & Catherine VanDercreek Professor, Florida State University College of Law.

Introduction

Two ideological struggles played out between the East and West from the late 1940s until the late 1980s: a political one—between proponents of authoritarian and democratic ideals; and an economic one—between proponents of market-based and centrally planned economies.[1] Socialist economies were associated with a top-down approach, in which planners, designers, and economic engineers played a vital role; capitalist economies, on the other hand, were associated with a bottom-up, anarchical approach involving "spontaneous order"[2] and "invisible hands," in which planners, designers, and economic engineers were sidelined in the name of increasing aggregate social welfare.[3] While the West clearly won the political battle, there were no clear victors in the realm of economic theory. Perfectly efficient markets turned out, in the end, to be as

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[1] *See generally* OSKAR LANGE & FREDERICK M. TAYLOR, ON THE ECONOMIC THEORY OF SOCIALISM (Benjamin Lippincott ed., 1938) (arguing for coordination through centralized, planned economies); F. A. Hayek, *The Use of Knowledge in Society*, 35 AM. ECON. REV. 519 (1945) (arguing that the dispersed information of atomistic actors does not require centralized planning since the information is, in essence, encapsulated in the "prices" that emerge in competitive markets).

[2] *See* Robert Sugden, *Spontaneous Order*, 3 J. ECON. PERSP. 85, 87 (1989) (describing Hayek's notion that institutions and order in a free society are "the unplanned consequences of a process of evolution"); Robert Nozick, *On Austrian Methodology*, *in* SOCRATIC PUZZLES 110, 111–18 (1997) (describing methodological individualism espoused by Austrian economists such as Carl Menger, Ludwig von Mises, and Hayek, and how it affects their beliefs on how institutions emerge and evolve over time); MICHAEL TAYLOR, THE POSSIBILITY OF COOPERATION 21–30 (1987) (developing argument regarding the provision of social order via market mechanisms).

[3] *See* Friedrich A. Hayek, *Engineers and Planners*, *in* THE COUNTER-REVOLUTION OF SCIENCE: STUDIES ON THE ABUSE OF REASON 165, 177–79 (1952) (drawing a distinction between engineers, who engage in conscious design, and markets, which are not "deliberately designed" but arise spontaneously to solve the problem of distributing and aggregating information about economic resources).

utopian as fully planned economies. It is now pretty well accepted that economic designers and engineers can help create value for society.[4] At the same time, bad engineering—poor design and implementation of contracts, markets, and legal rules—can reduce social welfare.

Modern financial firms are incredible feats of engineering, as are their products and the markets in which they are traded. The legal documents used in financial transactions, and the legal rules applicable to them, are also the product of conscious design.[5] For example, complex derivatives[6] are designed and valued using modeling, simulation,[7] and testing techniques developed by engineers[8] and statisticians to design, implement and monitor safety-critical[9] and autonomous systems,[10] such as nuclear reactors, air

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[4] *See infra* note 156 (discussing economists' work on mechanism design, which deals in part with the problem of creating contractual and institutional frameworks that approximate the workings of markets).

[5] *See* LON L. FULLER, THE PRINCIPLES OF SOCIAL ORDER: SELECTED ESSAYS OF LON L. FULLER 159–68 (Kenneth I. Winston ed., 1981) (discussing issues of institutional design and change, as applied to law, including discussing the legal design problem from a dynamic perspective).

[6] *See* FRANKLIN ALLEN & DOUGLAS GALE, FINANCIAL INNOVATION AND RISK SHARING 157–99 (1994) (describing optimal design process for securities); THOMAS S.Y. HO & SANG BIN LEE, THE OXFORD GUIDE TO FINANCIAL MODELING 332-65 (2004) (describing design process for complex derivatives).

[7] *See, e.g.*, PAUL GLASSERMAN, MONTE CARLO METHODS IN FINANCIAL ENGINEERING 1–3 (2004) (describing Monte Carlo methods and their use for simulating evolution of stochastic processes, and how this is in turn important for valuing derivative securities).

[8] *See* 1 CARLISS Y. BALDWIN & KIM B. CLARK, DESIGN RULES: THE POWER OF MODULARITY 64–77 (2000) (setting forth a number of good practices or "design rules" for designing and maintaining complex products).

[9] *See* HERMANN KOPETZ, REAL-TIME SYSTEMS: DESIGN PRINCIPLES FOR DISTRIBUTED EMBEDDED APPLICATIONS 271–81 (2d ed. 2011) (describing engineering issues involved in designing safety-critical, real-time systems).

[10] *See* Meryem Duygun Fethi & Fotios Pasiouras, *Assessing Bank Efficiency and Performance with Operational Research and Artificial Intelligence Techniques: A Survey*, 204 EUR. J. OPERATIONAL RES. 189 (2010); Wei-Yang Lin, Ya-Han Hu, & Chih-Fong Tsai, *Machine Learning in Financial Crisis Prediction: A Survey*, 42 IEEE TRANS. ON SYST., MAN & CYBERNETICS—PART C: APPLICATIONS & REV. 421 (2012); Feng Li, *The Information Content of Forward-Looking Statements in Corporate Filings—A Naïve Bayesian Machine Learning Approach*, 48 J. ACCT. RES.

traffic control systems, and the drones used by the military. These are systems that are inherently complex and require real-time monitoring. Given these commonalities, in recent years, universities have introduced graduate programs in financial mathematics and engineering, and investment banks have populated their security design departments with mathematicians, physicists, computer scientists, and others who are well-versed in modern engineering practices.[11]

The Great Recession of 2007-2009 can be characterized as a catastrophic engineering failure: financial institutions, financial markets, derivative products, valuation models, and legal regulations were improperly designed, implemented, and maintained.[12] There was too much complexity, too little transparency, and a paucity of

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1049 (2010) (using machine learning algorithm to analyze tone and content of forward-looking statements in corporate disclosures).

[11] *See* Robert A. Jarrow, *In Honor of the Nobel Laureates Robert C. Merton and Myron S. Scholes: A Partial Differential Equation That Changed the World*, 13 J. ECON. PERSP. 229, 238 (1999) (describing introduction of financial engineering programs in mathematics and engineering departments at Carnegie Mellon, Cornell, University of Chicago, University of Michigan and New York University, and stating that, as a result of the growth of financial derivatives, "mathematicians and physicists can now find alternate and high-paying demand for their skills on Wall Street").

[12] There is a long history of catastrophic failures due to engineering mistakes. Examples of engineering failures in the last thirty-five years include: the structural failure, in 1981, that led to the collapse of a suspended walkway in the Hyatt Regency in Kansas City; the release of toxic gases into the atmosphere by the Union Carbide pesticide plant in Bhopal, India, in 1984, which resulted in the death of several thousand people; the Chernobyl nuclear disaster, in 1986, due to faulty design of the nuclear reactor; and the Challenger space shuttle disaster, in 1986, caused by a faulty O-ring in one of the solid rocket boosters. *See* MARC GERSTEIN & MICHAEL ELLSBERG, FLIRTING WITH DISASTER, WHY ACCIDENTS ARE RARELY ACCIDENTAL 66-125 (2008) (providing overview of the Chernobyl and Challenger disasters); LEARNING FROM DISASTER: RISK MANAGEMENT AFTER BHOPAL 133 (Sheila Jasanoff ed., 1994) (describing the consequences of events in Bhopal, India). More recent examples of engineering failures include the Deepwater Horizon oil spill and the battery problems that led to the grounding of all of Boeing's 787 "Dreamliner" aircraft. *See generally* Michael Huerta, Fed. Aviation Admin., Address at Press Conference: Boeing 787 Design and Production Review (Jan. 11, 2013), *available at* http://www.faa.gov/news/speeches/news_story.cfm?newsId=14215.

timely monitoring by regulators and investors—at least as to this, there is broad consensus among regulators, commentators, and market participants.[13] But what exactly is "complexity" in this context? What is "transparency," and why is it valued so highly? And what are the real-time monitoring and governance constraints in the quickly changing environments in which financial institutions operate?

There are myriad ways of defining and measuring complexity and transparency. This matters because the definitions and metrics used will affect how regulators go about implementing the Dodd-Frank Act. Moreover, while large parts of the Act were adopted to provide the right incentives to managers, investors, and regulators to identify growing systemic risk on a more timely basis, we still do not have a good understanding of the relationship between complexity, transparency, and real-time governance, or of whether it is possible to identify and manage financial crises in real-time: before they have spread to other sectors of the economy or to other countries.

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[13] *See, e.g.*, THE COUNTERPARTY RISK MGMT. POLICY GRP. III, CONTAINING SYSTEMIC RISK: THE ROAD TO REFORM 55 (August 6, 2008), *available at* http://www.crmpolicygroup.org/docs/CRMPG-III.pdf (arguing that "lack of price transparency" is a common characteristic of complex derivatives, among other reasons because of the use of collateralized debt obligations that are specifically tailored to a small group of buyers and the fact that internal valuations often depend on "proprietary financial models and the inputs that drive those models"); THE PRESIDENT'S WORKING GRP. ON FIN. MKTS, POLICY STATEMENT ON FINANCIAL MARKET DEVELOPMENTS 4 (2008), *available at* http://www.treasury.gov/resource-center/fin-mkts/Documents/pwgpolicystatemktturmoil_03122008.pdf (proposing changes to increase transparency in rating process in securitizations); U.S. DEP'T OF THE TREASURY, FINANCIAL REGULATORY REFORM, A NEW FOUNDATION: REBUILDING FINANCIAL SUPERVISION AND REGULATION 6 (2009), *available at* http://www.treasury.gov/initiatives/Documents/FinalReport_web.pdf (stating that the crisis was due in part to the "lack of transparency" in securitization market which "prevented market participants from understanding the full nature of the risks they were taking"); U.S. SEC. & EXCH. COMM'N, TOWARD GREATER TRANSPARENCY; MODERNIZING THE SECURITIES AND EXCHANGE COMMISSION'S DISCLOSURE SYSTEM 3 (January 2009), *available at* http://www.sec.gov/spotlight/disclosureinitiative/report.pdf (stating that "modernizing the disclosure system will improve transparency by making disclosure information more accessible and easier to use").

The Article develops a theory of complexity and real-time transparency in financial systems. It also introduces techniques developed by engineers to manage complexity. Some of these, such as the use of modular design, have received attention from legal commentators. My aim is to provide a more detailed analysis of these methods, and to introduce others that have not received attention in the legal literature, particularly those dealing with the design, testing, and monitoring of real-time, safety-critical systems.

Part I sets forth a general overview of complexity and bounded rationality. It also examines the role of beliefs, expectations, and plans in dealing with complex environments. Part II extends this general understanding of complexity by introducing the concepts of intertemporal, coordination, strategic, and governance complexity. After doing so, it provides an overview of some of the standard techniques that can be used to address these forms of complexity. Part III then sets forth a detailed account of the complexity of financial institutions, financial contracts, and financial systems. Part IV analyzes various approaches used by engineers to design and implement complex systems. Part V begins by discussing three general timing issues in the governance of financial institutions and the monitoring of financial systems. It continues by specifying the relationship between complexity, bounded rationality, and transparency. The Part then argues that a financial system is essentially a real-time, safety-critical system, and analyzes various techniques used by engineers to design, test, and monitor such systems.

I. Complexity: General Background

This Part begins by providing a general overview of the problem of complexity and bounded rationality. It then analyzes the role played by beliefs, expectations, and plans in helping actors navigate through complex environments.

A. Complexity in Context

I will assume that a decision-maker wants to make decisions that will maximize the likelihood that she will achieve a specific goal, at the minimum cost.[14] Individuals make decisions within a

[14] These costs include monetary outlays, as well as intangible forms of disutility, such as exerting effort.

particular environment, and at a particular point in time.[15] The environment can be seen as everything outside an actor that is somehow relevant to the decision at hand. It is composed of other actors and tangible and intangible "things," including abstract concepts, such as those relating to time, logic, and strategy.[16] An environment's complexity is a function of the number of components in it and the way that they interact.[17] The latter is of critical importance in understanding and managing complex systems. For example, individuals fluent in the same language use a much larger set of signs to communicate with each other than do individuals who do not share a formal language and who are thus reduced to using hand and face gestures to say what they mean; the latter form of communication includes a smaller number of possible signs, but has a much higher level of complexity due to the indeterminate manner in which hand and face gestures map onto potential meanings.[18]

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[15] *See* JON BARWISE, THE SITUATION IN LOGIC, at xiv (1989) (developing "situation logic" in which actors find themselves within a context or situation—i.e., "portions of reality"—at a specific point in time).

[16] More generally, an environment can be characterized as a system—a set of components, each in some relation with others. Each of these components may be considered its own environment, to the extent that it is composed of other components, and so on until one bottoms out at a set of primitive components. This sort of compositional approach to "constructing" environments helps reduce their overall complexity. *See* C.A.R. HOARE, COMMUNICATING SEQUENTIAL PROCESSES 45 (2004) (stating that compositional design helps reduce complexity of reasoning about complex concurrent systems by treating equally all relationships between observer and environments, and arguing that a "complete system should also be regarded as a process, whose range of behaviour is definable in terms of the behaviour of its component processes; and the system may in turn be placed within a yet wider environment").

[17] Herbert Simon defined a complex system as "one made up of a large number of parts that have many interactions," where its complexity will increase because, "given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole." HERBERT A. SIMON, THE SCIENCES OF THE ARTIFICIAL 183–84, 207 (3d ed. 1996).

[18] One way to reduce the complexity of translating between two languages is to reduce the set of possible interpretations by imposing greater structure to the process of translation. *See* WILLARD VAN ORMAN QUINE, WORD AND OBJECT 28–30 (1960) (introducing the general problem of indeterminacy of translation when someone is engaged in a complete, or radical translation between two languages, using the example a native speaker in one language

More generally, if environments *A* and *B* have the same number of components but the interactions between *A*'s components are not as well calibrated or involve deeper, less transparent interconnections, then *A* will be more complex than *B*. It follows that one can reduce *A's* complexity by making the interconnections between its components more salient and understandable.[19]

The greater the complexity, the greater the computational and interpretive difficulties (i.e., the cognitive load or psychic cost that a decision-maker must expend to make sense of an environment or group of objects).[20] Given that not all individuals will be equal to the task, the level of complexity of an environment will depend on an additional factor: the identity of the individual who is trying to make sense of it. Individuals will differ vis-à-vis their previous experience with an environment and general ability to process information—their level of "cognitive efficiency."[21] A ten-year-old and an adult reading Tolstoy's *War and Peace* will no doubt experience different levels of cognitive load. And a contract that is straightforward to the party who drafted it may appear complex to the other party or a judge.

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referring to a rabbit scurrying by and a translator trying to make sense of the various possible interpretations); DONALD DAVIDSON, *Truth and Meaning*, *in* INQUIRIES INTO TRUTH & INTERPRETATION 17, 27 (1984) (introducing theory of radical interpretation which resolves, at least in part, Quine's indeterminacy of translation problem by requiring the translator to apply a rule of charity that tries to maximize the level of agreement between the two languages).

[19] *See* SIMON, *supra* note 17, at 215 ("How complex or simple a structure is depends critically upon the way in which we describe it. Most of the complex structures found in the world are enormously redundant, and we can use this redundancy to simplify their description. But to use it, to achieve the simplification, we must find the right representation.").

[20] *Id.* at 38 ("[L]imits on human abilities to compute scenarios of complex interaction prevent an infinite regress of mutual outguessing.").

[21] One way to model different observers is to identify the properties that are important for the purpose at hand, and use these to divide them into different "types." As we will see, this process of partitioning a set along types is just one way of managing complexity—in this case, the complexity faced by someone designing or evaluating a complex system involving actors with different properties. *See, e.g.*, MARTIN J. OSBORNE & ARIEL RUBINSTEIN, A COURSE IN GAME THEORY 231–32 (1994) (using "types," in context of game theory, to distinguish between players with different properties or different information sets); MICHAEL L. SCOTT, PROGRAMMING LANGUAGE PRAGMATICS 320–30 (2000) (describing role played by types in reducing the complexity of large computer programs).

B. Bounded Rationality

A fully rational actor who has determined that the benefits of using a piece of information exceed the costs will take the time and effort to process and use that information. But unlike these idealized, fully rational actors, real-world decision-makers face time and computational constraints. Such boundedly rational actors will have to economize by filtering out or not using some of the information available to them.[22] One approach to reducing the cognitive load needed to make decisions within complex environments is to use "rules of thumb" or heuristics that are well suited for the task at hand.[23] When boundedly rational actors interact in a complex environment, heuristics and satisficing becomes the norm.[24] All other things being equal, the use of heuristics will increase with the complexity of the environment.[25]

But, using heuristics to manage complexity can have significant effects on the decision-making process and in some instances lead people to make decisions that systematically deviate from those made by otherwise identical, but fully rational actors.[26] It

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22 Simon's work in this area starts with the "observation that human thinking powers are very modest when compared with the complexities of the environments in which human beings live." HERBERT A. SIMON, MODELS OF THOUGHT 3 (1979) (describing "satisficing" decisions due to deliberation using only a subset of the available and relevant information set).

23 *See* SIMON, *supra* note 17, at 29 (describing the boundedly rational decision-maker as "a satisficer, a person who accepts 'good enough' alternatives, not because less is preferred to more but because there is no choice").

24 *See* HERBERT A. SIMON, ADMINISTRATIVE BEHAVIOR 243–44 (3d ed. 1976) (discussing the interaction between individual bounded rationality and group decision-making); SIMON, *supra* note 17, at 28 (arguing that a heuristic search is a powerful decision-making tool in the face of the complexity of business firms, which must be satisfied with finding "good enough answers to questions whose best answers are unknowable").

25 *See, e.g.*, John W. Payne, *Task Complexity and Contingent Processing in Decision Making: An Information Search and Protocol Analysis*, 16 ORG. BEHAV. & HUM. PERFORMANCE 366, 384 (1976) (showing that "increases in the complexity of a decision situation will result in decision makers resorting to choice heuristics in an effort to reduce cognitive strain").

26 *See* Amos Tversky & Daniel Kahneman, *Judgment Under Uncertainty: Heuristics and Biases*, *in* JUDGMENT UNDER UNCERTAINTY: HEURISTICS AND BIASES 3 (Daniel Kahneman, Paul Slovic & Amos Tversky eds., 1982)

can also lead to inconsistent decisions across similarly situated actors: two actors deliberating about the same decision using identical information sets may reach different results, to the extent that they use different heuristics or face different time and computational constraints.[27] Not surprisingly, bounded rationality has received a large amount of attention from commentators in disciplines in which understanding and predicting the behavior of decision-makers matters: psychology,[28] economics,[29] computer science,[30] and the law.[31]

(arguing that heuristics have benefits and costs, and can lead to systematic—i.e., non-random—deviations from rational behavior).

[27] This means that one approach is to leave the level of complexity alone and instead reduce temporal constraints and/or supplement human computational power with that of a computer. This has become an increasingly attractive possibility given recent improvements in computer memory storage and processor power, developments in peer-to-peer networks, and the proliferation of highly sophisticated financial management systems. *See, e.g.*, HERBERT A. SIMON, THE SHAPE OF AUTOMATION: FOR MEN AND MANAGEMENT 49 (1965) (describing the role that computers can play in managing corporations).

[28] *See, e.g.*, Giovanni Dosi & Dan Lovallo, *Rational Entrepreneurs or Optimistic Martyrs? Some Considerations on Technological Regimes, Corporate Entries, and the Evolutionary Role of Decision Biases*, *in* TECHNOLOGICAL INNOVATION: OVERSIGHTS AND FORESIGHTS 41, 42–43 (Raghu Garud et al. eds., 1997) ("In economics, the use of psychological assumptions other than rationality to make predictions about organizational behavior is relatively rare, although the company is quite good . . . ."). *See generally* JUDGMENT UNDER UNCERTAINTY: HEURISTICS AND BIASES (Daniel Kahneman, Paul Slovic & Amos Tversky eds., 1982) (describing how psychologists approach the study of judgment).

[29] ARIEL RUBINSTEIN, MODELING BOUNDED RATIONALITY 107–20 (1998) (discussing various approaches to modeling bounded rationality within groups).

[30] *See, e.g.*, STUART J. RUSSELL & PETER NORVIG, ARTIFICIAL INTELLIGENCE: A MODERN APPROACH 845–46 (1995) (discussing challenge of bounded rationality for artificial intelligence).

[31] This problem of bounded rationality and cognitive load is now firmly embedded in the legal vocabulary. *See, e.g.*, Christine Jolls, Cass R. Sunstein & Richard Thaler, *A Behavioral Approach to Law and Economics*, 50 STAN. L. REV. 1471, 1477–78 (1998) (discussing bounded rationality and heuristics issues within legal context).

C. Using Beliefs and Expectations to Navigate Through Complex Environments

An actor will choose a course of action based on a set of beliefs regarding the current state of the decision environment, and her expectations of how her actions will affect that environment. More specifically, the actor will approach her environment with certain pre-conceived beliefs[32]: about its contents, its current state, and the likelihood that it will evolve into a different state. She will also approach the environment with a pre-defined "language" that she will use to try to make sense of it: a set of syntactical rules identifying its primitive components and the various ways that she can combine these; and a semantics—a set of rules that allows her to attach meanings to the primitive and composite components of her environment.[33] This will often require a decision-maker to make preliminary observations and interpretations, which will allow her to form contingent beliefs,[34] which she will revise as she continues to deliberate and interact with her environment.[35] A decision-maker's

[32] A belief is a type of disposition to assent to certain propositions about it. If *A* believes that *X* is true then *A* would assent to the following proposition: "*X* is true." To say that *A* believes that Napoleon lost at Waterloo, just means that *A* has the disposition to answer yes if asked, "Did Napoleon lose at Waterloo?" *See* WILLARD VAN ORMAN QUINE & JOSEPH SILBERT ULLIAN, THE WEB OF BELIEF 11 (2d ed. 1978) (stating that a person has belief *X* if it has a disposition to assent to questions regarding those beliefs). More generally, one can say that a proposition such as "it is snowing" is true if and only if it is now snowing in the environment in question. For such a definition of truth, see ALFRED TARSKI, *The Concept of Truth in Formalized Languages*, *in* LOGIC, SEMANTICS, METAMATHEMATICS 152, 156 (J.H. Woodger trans., 1956) ("[I]t is snowing is a true sentence if and only if it is snowing.").

[33] Languages extend beyond the spoken and written word, to encompass myriad types of symbols and ways of sending meaningful signals. What ultimately matters is that the person using a language uses the grammar and semantics of that language in a consistent manner.

[34] *See* BARWISE, *supra* note 15, at 5 (stating that knowledge and beliefs regarding the world depend on those parts of the world with which an agent interacts).

[35] *See* Radu J. Bogdan, *The Manufacture of Belief*, *in* BELIEF: FORM, CONTENT AND FUNCTION 149, 160–61 (Radu J. Bogdan ed., 1986) (stating that beliefs "track" certain facts or information about the real world); ROBERT NOZICK, THE NATURE OF RATIONALITY 67–70 (1993) (discussing various reasons for privileging true beliefs, and identifying specific contexts

beliefs and expectations,[36] and her attachment to them, can greatly influence her ability to navigate[37] through complex environments;[38] they allow her to face familiar events and occurrences without having to re-invent the wheel.[39] Beliefs and expectations are

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in which having true beliefs can undermine other goals held by an individual).

[36] The notion of "expectations" is one that is prevalent in many different academic literatures, including cognitive psychology, artificial intelligence, linguistics, sociology, and economics, although they each use the term in slightly different ways. *See, e.g.*, ERVING GOFFMAN, FRAME ANALYSIS 10–11 (1974) (using the word "frame" to study "the organization of experience," the definition of situations, as they are "built up in accordance with principles of organization which govern events—at least social ones—and our subjective involvement in them"); ROGER C. SCHANK & ROBERT P. ABELSON, SCRIPTS, PLANS, GOALS & UNDERSTANDING: AN INQUIRY INTO HUMAN KNOWLEDGE STRUCTURES 36–42 (1977) (relating the importance of expectations in scripts, defined as "a predetermined, stereotyped sequence of actions that defines a well-known situation"); Deborah Tannen, *What's In A Frame? Surface Evidence for Underlying Expectations*, *in* FRAMING IN DISCOURSE 14, 14–21 (Deborah Tannen ed., 1993) (discussing the role played by "expectations" as an ordering device, a way of allowing us to make sense of new information given our prior belief); Amos Tversky & Daniel Kahneman, *Rational Choice and the Framing of Decisions*, *in* DECISION MAKING: DESCRIPTIVE, NORMATIVE, AND PRESCRIPTIVE INTERACTIONS 167, 172 (David E. Bell et al. eds., 1988) (stating that "framing" is affected, among other things, by "the norms, habits, and expectancies of decision makers").

[37] *See* FRANK RAMSEY, THE FOUNDATIONS OF MATHEMATICS AND OTHER LOGICAL ESSAYS 238 (1931) (arguing that a "belief of the primary sort is a map of the neighbouring space by which we steer").

[38] *See* NOZICK, *supra* note 35, at 98 (discussing how, in certain contexts, a background framework of beliefs is taken for granted); Tannen, *supra* note 36, at 20–21 (stating that individuals approach the world "as experienced and sophisticated veterans of perception who have stored their prior experiences as 'an organized mass,' and who see events and objects in the world in relation to each other and in relation to their prior experience"); Robert N. Ross, *Ellipsis and the Structure of Expectations*, 1 OCCASIONAL PAPERS IN LINGUISTICS 183 (1975) (referring to an individual's "structure of expectations" as the way individuals (1) organize knowledge about the world and (2) use that knowledge to process new information, events, and experiences; and stating that these expectations are based on one's prior experiences about the world).

[39] *See* Tannen, *supra* note 36, at 21 ("This prior experience about the world, and in the vast majority of cases, the world, being a systematic place,

particularly important when individuals interact with each other in social contexts. They allow individuals to communicate, to make sense of each other and avoid misunderstandings,[40] and, as a result, to coordinate their behavior.

D. Using Plans to Manage Complexity

Plans are useful devices for managing complexity.[41] That is, when individuals are faced with coordinating their actions over time, they can resort to planning as a way to decompose the decision space into smaller, more manageable pieces.[42] Planning, therefore, allows individuals to mediate between the present and the future, in a world of bounded rationality,[43] thereby allowing them to undertake more complex tasks.[44] When someone makes a plan, she makes a contingent commitment as to her future behavior.[45] If the problem space is large and complex, the individual may divide the plan into smaller, more manageable sub-plans that she can execute sequentially or, in certain cases, concurrently.[46] In the end, plans are defeasible in the sense that they are "soft," but not fully binding

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confirms these expectations, saving the individual the trouble of figuring things out anew all the time.").

[40] *See* GOFFMAN, *supra* note 36, at 496–499 (discussing the role of "frames" in facilitating communication, dealing with ambiguities, and avoiding misunderstandings).

[41] *See* MICHAEL E. BRATMAN, INTENTIONS, PLANS, AND PRACTICAL REASON 10–11 (1987) (discussing the problem of decision-making by individuals given bounded rationality and the role of planning in reducing the bounded rationality constraint).

[42] *Id*. at 30 (discussing how through planning "our deliberation and our actions is [sic] systematically extended over time").

[43] *See* Michael E. Bratman et al., *Plans and Resource-Bounded Practical Reasoning*, *in* PHILOSOPHY AND AI 7, 7–8 (Robert Cummins & John Pollock eds., 1991) (discussing the fact that, given bounded rationality, deliberation will take time (which increases as the complexity of the task increases) and that the world about which an individual is deliberating will tend to change during the time in which she is engaged in deliberation).

[44] *See* BRATMAN, *supra* note 41, at 28 (discussing the role of planning in allowing individuals to undertake more complex tasks).

[45] *Id*. at 29 (defining "plans" as "mental states involving an appropriate commitment to action: I have a plan to *A* only if it is true of me that I plan to *A*").

[46] *Id*. (arguing that plans are usually filled out over time and that they are often embedded in a hierarchical fashion).

commitments—we may decide not to follow through with a plan, or to act in a different manner.[47] A plan is like an option that we may or may not exercise; like an option, there is some value attached to tacitly (but not fully) committing to a course of action, knowing that we can always change our minds.

II. Domain-Specific Complexity

Designing a system to reduce complexity and create transparency is itself a complex task. One way to help reduce this second-order problem is to decompose the concept of complexity into a set of simpler, and self-contained, types of complexity that are applicable to specific domains or environments. This Part analyzes the domain-specific complexity involved in the corporate governance of firms in the real and financial sectors. In doing so, it introduces the concepts of intertemporal, coordination, strategic, and governance complexity. This will provide a framework for the analysis, in Part III, of the complexity of financial institutions, financial contracts, and the financial system more generally.

A. Intertemporal Complexity

One can draw a distinction between static or one-shot decisions and intertemporal ones, in which the behavior of actors in one period can cast a shadow over the future. The static complexity of a particular decision will depend on the number of participants involved and the nature of their interactions.[48] It will also depend on the complexity of the information used in the process.[49] When actors

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[47] *Id*. at 32.

[48] In some instances, a decision-maker is able to isolate a decision at time *t* from those that occurred before by assuming that all relevant information about past behavior is incorporated into the information set held by the decision-maker at time *t*. *See* KENNETH B. KAHN, NEW PRODUCT FORECASTING: AN APPLIED APPROACH 63–67 (2006) (describing Markov processes).

[49] *See* KENNETH J. ARROW, THE LIMITS OF ORGANIZATION 53–59 (1974) (discussing the role of information channels and communication codes within organizations to deal with informational complexity); Michael C. Jensen & William H. Meckling, *Specific and General Knowledge, and Organizational Structure, in* CONTRACT ECONOMICS 251 (Lars Werin & Hans Wijkander eds., 1992) (discussing the agency costs that arise when

make a decision, at time *t*, they must account for both static and dynamic (or intertemporal) complexity.[50] An intertemporal decision is one in which the consequences or payoffs accrue at different points in time.[51] In making an intertemporal decision, a rational actor will choose the course of action that maximizes the sum of her current and future well-being, given her beliefs as to how she expects to act in the future.[52] To do this, the actor will try to predict how her preferences and the environment will change over time. In a sense, one can view the decision in the current period as creating an externality on future ones; failing to take the externality into account

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actors use their control over knowledge and information to exercise power within organizations).

[50] The most common way to model dynamic environments is to posit that at any one point in time, the environment will be in a particular state, where a state is a description of a set of properties that are true of the environment at a particular point in time. As a general matter, a decision-maker will be interested in knowing only a subset of these true propositions. *See* ARROW, supra note 49, at 34 (stating that a decision-maker will "consider the world to be in one or another of a range of states," where a state of the world is "a description which is complete for all relevant purposes"); HARRY R. LEWIS & CHRISTOS H. PAPADIMITRIOU, ELEMENTS OF THE THEORY OF COMPUTATION 55–57 (2d ed. 1998) (describing computational approach of modeling dynamic objects as "automatons" defined by a set of states and a set of transitions from start to a terminal state); OSBORNE & RUBINSTEIN, *supra* note 21, at 143–49 (using automaton approach to model behavior of actors in infinitely repeated games).

[51] As a result, intertemporal decision-makers have to make tradeoffs between payoffs in different time periods. *See* George Loewenstein & Richard H. Thaler, *Intertemporal Choice*, 3 J. ECON. PERSP. 181, 181 (1989) (defining intertemporal choices as "decisions in which the timing of costs and benefits are spread out over time"); George F. Loewenstein & Drazen Prelec, *Preferences for Sequences of Outcomes*, *in* CHOICES, VALUES, AND FRAMES 565, 565 (Daniel Kahneman & Amos Tversky eds., 2000) ("Decisions of importance have delayed consequences."). For a general discussion of various roles played by time in decision-making, see Dan Ariely & Dan Kakay, *A Timely Account of the Role of Duration in Decision Making*, 108 ACTA PSYCHOLOGICA 187–207 (2001) ("[I]t takes time to make decisions and sometimes the decisions dynamically change with the passage of time.").

[52] *See* Ted O'Donoghue & Matthew Rabin, *Choice and Procrastination*, 116 Q.J. ECON. 121, 128 (2001) (setting up a general model where people act with reasonable beliefs about future actions and choose current actions to maximize their intertemporal utility in light of those beliefs).

can therefore lead to distortions in the decision-making process.[53] For example, a manager who makes a false disclosure in violation of the securities laws may find that she will need to repeat that false statement in subsequent filings and supplement it with additional ones in order to prevent shareholders and regulators from discovering the initial violation. One would expect that over time the complexity faced by that manager will increase, given that she will have to make more elaborate and interrelated false statements.

First, complexity will increase with the number of time periods involved, the length of each one, and the manner in which those periods are interrelated. There are three principal factors that affect the level of intertemporal complexity of a decision. The first factor is the number of time periods that the decision-maker has to incorporate into her cost-benefit analysis. For example, longer time periods will tend to increase the level of complexity by increasing the number of considerations or contingencies that the decision-maker will have to account for. A decision about one's retirement will be more complex than a decision made at breakfast about what to cook for dinner. The second factor is the identity of the decision-maker and her familiarity with the domain in question. An investment banker making a portfolio allocation decision for a retirement plan faces a lower level of complexity than an individual with no prior experience in finance. The third factor influencing intertemporal complexity is the availability of mechanisms, whether tangible or conceptual, that allow a decision-maker to order and combine temporal components into "decision objects" that are easy to comprehend and use. Even when these mechanisms are available, an actor may decide to hire an expert who can piece through the complexity in a more efficient manner.

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[53] A negative externality is an action by one party that harms a second party, where the first party does not bear the full cost of her actions—e.g., when a factory releases pollutants into the atmosphere without bearing any environmental law sanctions. Similarly, an individual's behavior in the present can impose negative externalities on her future selves. *See* EUGENE SILBERBERG, THE STRUCTURE OF ECONOMICS: A MATHEMATICAL ANALYSIS 614–15 (1990) ("[W]here a decision in one time period affects the level of some relevant variable in the future . . . each decision imposes an 'externality' on the future."); R. J. Herrnstein et al., *Utility Maximization and Melioration: Internalities in Individual Choice*, 6 J. BEHAV. DECISION MAKING 149, 150 (1993) (referring to an externality between a person's current and future selves as an "internality").

A more extensive example will help make more concrete the role played by intertemporal complexity. Suppose that an individual is making a series of intertemporal decisions in which she has to make tradeoffs between current and delayed consumption; the latter involves investing funds in the present in the hopes of producing a large enough return in the future to offset the disutility from having to delay her consumption. This decision domain is one that comprises a large number of components, both static and variable. The set of possible investments includes not only stocks, bonds, and other standard securities, but also a number of more exotic derivative products, each of which may be traded in organized exchanges or over-the-counter. The individual can also invest in other types of assets: real estate, commodities, and her own human capital. She will also have a large number of consumption goods to choose from in the current and in future periods. In addition to these external features of her environment, the individual will need to make sense of her own self—her current preferences, and how these may evolve, as well as her tolerance for risk.

As can be seen, even a relatively straightforward decision—choosing what to consume and when, and how to invest one's funds—can involve a great deal of complexity. The general problem becomes even more complex when the individual is called to make decisions affecting others—decisions within a household or a corporation—and over longer periods of time—decisions about how much to save for retirement or, in the case of a corporation, how much to invest in research and development. For example, suppose that an individual is trying to decide how to allocate the flow of cash and other assets that she will receive and enjoy over her lifetime, where her underlying goal is to maximize the returns on her investments, given her risk preference, and the utility that she will receive from using them for consumption or leaving them to her heirs. While such a lifelong planning scenario may appear fanciful, given the obvious complexity involved, it is an important problem that has received a lot of attention from economists.[54]

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[54] Under the standard intertemporal model in macroeconomics, as well as certain areas of microeconomics, an actor has the following decision problem: maximize the sum of the instantaneous utility that she will receive over her lifetime, taking into account uncertainty, changes in preference, outside shocks to her income stream, and myriad other informational problems. *See* Stefano DellaVigna, *Psychology and Economics: Evidence*

B. Coordination Complexity

Some intertemporal decisions require a decision-maker to predict how other actors will act in the future. For example, financial intermediaries, their customers, and regulators are involved in a series of interconnected intertemporal relationships, not just with each other but also with their past and future selves.[55] In order to achieve coordination,[56] they need to assure that their behavior over time intersects along a number of dimensions— not just physically and temporally but also at the epistemic level.[57] Achieving

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from the Field, 47 J. ECON. LIT 315, 316–17 (2009) (discussing lifetime intertemporal utility model, including its limitations).

[55] Economists sometimes model an intertemporal decision-maker as (1) a current self with current preferences, and (2) a series of separate "agents," one for each point in time between current choices and future consequences, which collectively constitute the decision-maker's "future selves." The current agent will make choices to maximize her current preferences, but her future selves will control her behavior. *See* Ted O'Donoghue & Matthew Rabin, *Doing It Now or Later*, AM. ECON. REV., Mar. 1999, at 103, 106 ("The person at each point in time is modeled as a separate 'agent' who is choosing her current behavior to maximize current preferences, where her future selves will control her future behavior."); Roland Bénabou & Jean Tirole, *Self-Knowledge and Self-Regulation: An Economic Approach*, *in* 1 THE PSYCHOLOGY OF ECONOMIC DECISIONS 137–38 (Isabelle Brocas & Juan D. Carrillo eds., 2003) (arguing that actors "who usually populate economic models have little doubt about 'who they are': they know their own abilities and basic preferences"); Derek Parfit, *Personal Identity*, 80 PHIL. REV. 3, 26–27 (1971) (arguing that individuals discount future payoffs because of changes in identity over time—a diminution of the connection between our present and future selves).

[56] *See* DREW FUNDENBERG & JEAN TIROLE, GAME THEORY 18–20 (1991) (providing formal treatment of coordination games); DAVID HUME, A TREATISE OF HUMAN NATURE 489–90 (L.A. Selby-Bigge ed., Oxford Univ. Press 1978) (1888) (classic treatment of coordination problem and contracting relationships); THOMAS C. SCHELLING, THE STRATEGY OF CONFLICT 54–57 (1960) (describing the role of focal points in overcoming coordination problems). See generally DAVID K. LEWIS, CONVENTION: A PHILOSOPHICAL STUDY (1969) (discussing coordination problem from a philosophical perspective and developing the concept of common knowledge).

[57] This general problem of epistemic coordination within organizations has received close attention in the transaction cost, agency, and property rights literatures. *See* LUDWIG VON MISES, HUMAN ACTION: A TREATISE ON ECONOMICS 143–45 (Ludwig von Mises Inst. Scholar's ed. 1998) (1949)

coordination along these three dimensions is not a straightforward exercise; instead, it is one fraught with the potential for failure, which can be costly, even if it is only temporary in nature.[58] The ability of actors to coordinate their behavior will depend on the complexity of the environment in which their cooperative activities take place. Coordination will become more difficult to the extent that actors have incomplete information about each other and their environment. The problem is further exacerbated if their behavior is guided by complex legal rules and contracts. Having said that, properly tailored rules and contracts, as well as formal organizations such as corporations, can help focus the actors' attention on the proper modes of achieving coordination. [59]

C. Strategic Complexity

The intertemporal and coordination complexity problems discussed in the previous two sections make it easier for parties to act opportunistically; that is, to take advantage of counterparties who make reliance investments or who are at an informational disadvantage. Parties who are contemplating entering into a

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(discussing the causes of human cooperation); OLIVER E. WILLIAMSON, MARKETS AND HIERARCHIES 31–33 (1975) (discussing "information impactness"—i.e., "when true underlying circumstances relevant to the transaction . . . are known to one party but cannot be costlessly discerned by or displayed for others," given uncertainty, opportunism, and bounded rationality (citation omitted)).

[58] *See* Manuel A. Utset, *Towards a Bargaining Theory of the Firm*, 80 CORNELL L. REV. 540 (1995) (arguing that an important role of corporate governance is to reduce the costs associated with these sorts of coordination failures and bargaining breakdowns).

[59] Potential coordination failure plays an important role in business firms generally. *See* CHESTER I. BARNARD, THE FUNCTIONS OF THE EXECUTIVE 6 (1958) (arguing that "the survival of an organization depends upon the maintenance of an equilibrium of complex character in a continuously fluctuating environment . . . which calls for readjustment of processes internal to the organization") (citation omitted); SIMON, *supra* note 24, at 72 (stating that "cooperation will usually be ineffective—will not reach its goal, whatever the intentions of the participants—in the absence of coordination"); R. H. Coase, *The Nature of the Firm*, *in* 4 ECONOMICA 386 (1937), *reprinted in* THE FIRM, THE MARKET, AND THE LAW 33, 35–36 (1988) (arguing that within the firm, market mechanisms are replaced by an "entrepreneur-co-ordinator" who makes production decisions).

transaction and who are worried about the potential opportunistic behavior of their counterparty will need to try to predict the likelihood that certain states of the world will arise that will allow that other party to take advantage of informational asymmetries or of changes in the bargaining power between them. Strategic complexity will thus depend on the level of uncertainty about how the environment will evolve and how counterparties will behave; as a result, it will also depend on the complexity of the information needed to make predictions and identify risks as they materialize.

Suppose that a corporation needs to raise funds to finance a new project. It can either use internally generated cash flows, borrow from a bank, or sell debt or equity securities to investors.[60] Potential investors will need to distinguish between corporations that have valuable, viable projects, and those that have overvalued projects—in the sense that the managers have led investors to believe that the projects have higher expected cash flows that they actually do.[61] This screening task becomes more difficult the greater the informational asymmetries involved, and, all other things being equal, the latter will increase with the complexity of the project and of the borrower.[62] To the extent that good and bad corporations are pooled together, investors will require a higher return—to protect themselves against the possibility that they are buying into a "lemon"; this in turn can lead corporations with good projects either

[60] Securities are a special type of financial asset, useful both for making capital infusions and for valuing a firm's assets. *See* HO & LEE, supra note 6, at 17 (stating that financial assets are used to value real assets). Debt securities create a liability on the firm's balance sheet, or a claim on the firm's assets; common stockholders have a claim on any assets left after all of the firm's liabilities have been paid. *See* JEAN TIROLE, THE THEORY OF CORPORATE FINANCE 75–76 (2006) (comparing the rights and priority of distribution of debt and equity securities, and with regards to the latter, between common and preferred stock).

[61] *See* TIROLE, *supra* note 60, at 237 (discussing role of informational asymmetries and strategic behavior when firms are trying to raise funds from investors to finance new projects).

[62] Since debt has priority over equity, the level of strategic complexity faced by shareholders is greater than that faced by lenders and debtholders. *See, e.g.*, Stewart C. Myers, *The Capital Structure Puzzle*, 39 J. FIN. 575, 581 (1984) (arguing that firms will have incentive to finance new projects using internal financing, then debt, finally equity).

to abandon them or to finance them with internal cash flows.[63] These dynamics, generally referred to as the adverse selection (or "market for lemons") problem,[64] can lead to either total market failure—where investors withdraw from the market altogether—or an increase in the cost of capital for corporations with good projects.[65] Federal securities laws help reduce the adverse selection problem by increasing the costs faced by issuers of making false disclosures and requiring them to hire independent accountants to audit their financial statements, both of which make it more difficult for a bad corporation to pass itself off as a good one. [66]

After an investor has made a capital contribution it will still be subject to the potential strategic behavior of managers, who may use corporate funds to pay themselves higher salaries or engage in other types of self-dealing.[67] As the level of informational

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[63] Requiring a higher return on their investment is only a partial solution, given that after a cut-off point a corporation with a good project may be better off abandoning it, while bad corporations will be willing to offer the higher return, knowing that if the bad project does not work out, they can file for bankruptcy. *See, e.g.*, Joseph E. Stiglitz & Andrew Weiss, *Credit Rationing in Markets with Imperfect Information*, 71 AM. ECON. REV. 393, 394–97 (1981) (describing credit rationing due to adverse selection problem and attempts to deal with it by raising interest rates, an approach that can lead good borrowers to exit the market).

[64] *See* George Akerlof, *The Market for Lemons: Qualitative Uncertainty and the Market Mechanism*, 84 Q.J. ECON. 488, 489–90 (1970) (setting forth standard treatment of adverse selection problem in context of used car dealers, which have informational advantage over potential purchases of "lemons").

[65] *See* David Easley & Maureen O'Hara, *Price, Trade Size, and Information in Securities Markets*, 19 J. FIN. ECON. 69, 70 (1987) (stating that adverse selection reduces liquidity because potential buyers discount for the risk that sellers have private information).

[66] *See* Benjamin E. Hermalin & Michael S. Weisbach, Transparency and Corporate Governance 1 (Jan. 21, 2007), *available at* http://ssrn.com/abstract=958628 (unpublished manuscript) (discussing role of transparency in reducing cost of trading and thus firm's cost of capital).

[67] More generally, whenever one individual acts on behalf of another, a potential agency problem arises: the agent—the person acting—will undoubtedly have interests incongruous with those of her principal. All other things being equal, one would expect that a bona fide, self-interested agent will act in a self-serving manner, at least to the extent to which the principal cannot observe her behavior. *See, e.g.*, Joseph E. Stiglitz, *Principal and Agent*, *in* THE NEW PALGRAVE: ALLOCATION, INFORMATION

complexity increases, so will the costs of monitoring managers.[68] This type of informational asymmetry problem, arising after parties have entered into a transaction, is referred to as the "moral hazard" problem.[69] It is generally impossible to completely eliminate the problem—i.e., in most instances, the presence of moral hazard will lead to a second-best, or sub-optimal, solution.[70]

D. Governance Complexity

In designing governance rules to reduce intertemporal, coordination, and strategic complexity, regulators and private parties have to confront a fourth complexity constraint: the complexity of governance regimes themselves. One source of governance complexity is that associated with introducing additional actors into a system. For example, a regulator considering a legal rule to increase the transparency of corporate disclosures will need to have a sense of how managers and shareholders come to comprehend the complex environment in which they are situated. More generally, if observer *A*—a shareholder or manager—faces a complex environment, *E*, a regulator will face a larger and potentially more complex environment. This is because the complexity of that composite environment is a function of (1) two non-trivially complex

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AND MARKETS 241, 241–43 (John Eatwell et al. eds., 1989) (discussing the sources of agency problems in the credit relationship and various approaches available to try to reduce agency costs).

[68] *See* Michael C. Jensen & William H. Meckling, *Theory of the Firm: Managerial Behavior, Agency Costs and Ownership Structure*, 3 J. FIN. ECON. 305, 308–09 (1976) (discussing monitoring cost in principal-agent relationships).

[69] *See* TIROLE, *supra* note 60, at 16–18 (describing the moral hazard problem arising from informational asymmetry, which can allow managers to act in a self-serving fashion, at the expense of shareholders and debtholders).

[70] As with the adverse selection problem, requiring a higher rate of return is only a partial solution. If an investor asks for too much, the manager may decide not to do the deal at all; and if the investor requires too low a return it will dilute the manager's incentive to exert the effort necessary to maximize the returns from the asset. *Id.* at 115–24 (setting forth an agency model in which transactions are structured to meet a manager's participation constraint and to give her a sufficiently large portion of the project's expected returns, so that she has an incentive to act in the principal's best interest).

components—observer *A* and environment *E*; (2) the manner in which those components interact; and (3) the way that the regulator interacts with the complexity posed by (1) and (2).

A second source of governance complexity is the number of legal[71] and contractual rules that are used in a transactional or governance context; all other things being equal, governance complexity will increase with the number of rules. The level of complexity will also depend on the way that rules interact with each other and the identity of the actor who is trying to make sense of a governance rule. Contractual rules and legal regulations do not always interact in a transparent manner, particularly if those interactions occur in the shadow of markets, which may or may not be fully efficient. [72] Moreover, all other things being equal, a repeat player in a particular type of transaction will face a lower complexity constraint than would a consumer or inexperienced transacting party. It follows that designing legal rules to protect consumers is difficult, in part, due to this "complexity asymmetry" between the repeat players being regulated and the consumers being protected.

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[71] For a discussion of the complexity of legal rules, see Louis Kaplow, *A Model of the Optimal Complexity of Legal Rules*, 11 J.L. ECON. & ORG. 150 (1995) ("Legal rules often are complex in order to distinguish different types of behavior that may have different consequences.").

[72] In a perfectly efficient market, the equilibrium market price at a particular point in time will incorporate all relevant information; as a result, efficient markets help reduce complexity by allowing parties to ignore additional sources of information. *See* Hayek, *supra* note 1; HERBERT SIMON, ECONOMICS, BOUNDED RATIONALITY AND THE COGNITIVE REVOLUTION 27 (1992) (arguing that markets allow atomistic economic actors to conserve information, and thus "to behave rationally with relatively simple computations and on the basis of relatively little information"; and concluding that markets "make it possible for people of bounded rationality to make reasonable choices"). But when a market is not efficient, the level of complexity increases, as does the potential for complexity-driven market failures. *See, e.g.,* Randall Dodd, *Subprime: Tentacles of a Crisis*, FIN. & DEV., Dec. 2007, at 15 (stating that mortgage-back security misvaluations in the period leading to Great Recession of 2007 were caused in part by the fact that the "price discovery process is not transparent, and there is no surveillance in the market to identify where there are vulnerable positions").

E. Standard Approaches for Dealing with Intertemporal, Coordination, Strategic, and Governance Complexity

One way for investors to deal with strategic complexity is to monitor managers. Investors can engage in "active monitoring," which is forward-looking in that it attempts to increase the future value of the firm, or in "speculative monitoring," which is backward-looking.[73] Speculative monitoring takes a snapshot of the present state in order to determine what action to take: to sell stock, to call a loan, or to bring a lawsuit.[74] As we have seen, all other things being equal, the adverse selection and moral hazard problems will increase in severity as the information in question becomes more complex. The greater the complexity, the greater the costs of active and speculative monitoring. This in turn can exacerbate the well-known collective action problems faced by the shareholders of public corporations.

A second way for investors to deal with complexity is to use informational and complexity intermediaries. Financial institutions, such as banks, investment banks, insurance companies, hedge funds, and private equity funds, are in the business of acting as financial intermediaries: they help put together investors with corporations that need to raise funds.[75] In other words, corporations can raise capital either by selling securities in the capital markets[76] or by using

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[73] *See* Philippe Aghion et al., *Exit Options in Corporate Finance: Liquidity Versus Incentives*, 8 REV. FIN. 327, 331–33 (2004) (developing a corporate governance model that draws distinctions between active and speculative monitoring and in which speculative monitoring has no intrinsic value).

[74] *See* TIROLE, *supra* note 60, at 28 (stating that derivative and class-action lawsuits are forms of speculative monitoring based on past information and not meant to "enhance future value, but rather to sanction past underperformance").

[75] More generally, financial intermediaries transform one type of financial claim into another by entering into financial contracts with investors and corporations that need capital. *See* XAVIER FREIXAS & JEAN-CHARLES ROCHET, MICROECONOMICS OF BANKING 15 (2d ed. 2008) (stating that financial intermediaries specialize in purchasing and selling financial contracts, such as securities, and transforming illiquid assets into liquid ones).

[76] Even when companies raise funds by issuing securities, they will often use underwriters to act as informational intermediaries. *See* Stephen Choi, *Market Lessons for Gatekeepers*, 92 NW. U. L. REV. 916, 932 (1998)

financial institutions to help reduce the transactional risks associated with intertemporal, coordination,[77] and strategic complexity. As repeat players in investment projects, financial intermediaries are able to acquire the knowledge needed to evaluate potential projects and the managers who want to pursue them, and to monitor both of them after the fact.[78] For example, households can delegate these screening and monitoring tasks to banks, by depositing their savings, which the bank will aggregate and transform into loans.[79] Similarly, large institutional investors can delegate these tasks to venture capitalists, by investing in venture capital funds that will identify and invest in start-up firms and monitor the entrepreneurs.[80]

(discussing the role of underwriters in screening and in certifying information being provided by company).

[77] By relying on a financial intermediary, investors are able to reduce collective action and coordination problems. *See* Sudipto Bhattacharya et al., *Monitoring by and of Banks: A Discussion*, *in* CREDIT, INTERMEDIATION, AND THE MACROECONOMY 122, 122 (Sudipto Bhattacharya et al. eds., 2004) (stating that informational intermediaries are able to avoid free-rider concerns and reduce the coordination problems that beset decentralized investors in capital markets).

[78] *See* Charles Kahn & Andrew Winton, *Moral Hazard and Optimal Subsidiary Structure for Financial Institutions*, 59 J. FIN. 2531, 2553–54 (2004) (discussing the role of financial intermediaries, such as banks, in screening and monitoring borrowers on behalf of investors, who are at an informational disadvantage); Michael Rothschild & Joseph Stiglitz, *Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information*, 90 Q.J. ECON. 629, 648 (1976) (stating that the model of the insurance market in which there is informational asymmetry between the insured and insurance companies is similar to screening models); Ram T. S. Ramakrishnan & Anjan V. Thakor, *Information Reliability and a Theory of Financial Intermediation*, 51 REV. ECON. STUDIES 415 (1984) (discussing role of monitoring by coalitions of intermediaries).

[79] *See* Anjan Thakor, *Capital Requirements, Monetary Policy, and Aggregate Bank Lending: Theory and Empirical Evidence*, 51 J. FIN. 279, 293–94 (1996) (stating that one implication of the bank lending model developed in the article is that receiving a bank loan will send a positive signal to market, given the expectation that banks screen borrowers).

[80] At the time of making an investment in a start-up company, venture capitalists have incomplete information about its projects and whether the entrepreneur has the ability to become an effective manager. *See* Stephen N. Kaplan & Per Stromberg, *Characteristics, Contracts, and Actions: Evidence from Venture Capitalist Analyses*, 59 J. FIN. 2177, 2200 (2004) (discussing

Households can also turn to financial institutions to reduce the intertemporal and coordination complexity involved in making investments and consumption decisions over time. All other things being equal, households prefer to have liquid assets, which provide them with a "real option": they can wait until they have acquired more information about their liquidity preferences before making an illiquid long-term investment that is costly to reverse.[81] But liquidity comes at a cost, since it forecloses investments with potentially higher returns that require a commitment not to withdraw funds for a certain period of time.[82] Households can reduce their liquidity risks by lending money to a bank through a demand deposit account that can be terminated immediately and without penalty.[83] A bank can provide this type of liquid investment because it has a large number of depositors, and thus it can diversify its own liquidity risks due to the withdrawal of funds.

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role of staged investment in screening entrepreneurs). *See generally* Raphael Amit, Lawrence Glosten, & Eitan Muller, *Entrepreneurial Ability, Venture Investments, and Risk Sharing*, 36 MGMT. SCI. 1232 (1990) (setting forth an adverse selection model in the context of venture capital financing).

[81] People do not always know when in the future they will want to use their assets to purchase other assets or for consumption—e.g., making a different investment or going on a European vacation. *See* Jurgen Eichenberger & Willy Spanjers, *Liquidity and Ambiguity: Banks or Asset Markets?* 3 (Univ. of Heidelberg Discussion Paper Series, Paper No. 444, June 2007) ("Difficulties with liquidity provision arise from the inherent uncertainty about asset returns, but also from uncertainty about individual and aggregate liquidity needs."). As a result, a person who is uncertain about her future consumption preferences will want to allocate a portion of her assets to the higher paying illiquid investment while keeping a portion in liquid form—e.g., cash.

[82] For example, banks offer certificates of deposit which have higher returns than regular demand deposit accounts, but which have a penalty for early withdrawals. More generally, suppose that a consumer can invest in two types of projects: a one-year project with an assured return of $100 and a two-year project with an assured return of $150. The consumer has no other funds and is uncertain of whether she will have a preference to spend the $100 in year one. If she decides to opt for the one-year return of $100 and it turns out that she did not want to spend the money in year one, then she is foregoing $50. On the other hand, if she opts for the two-year project and wants to consume in year one, she will have a liquidity problem—i.e., she will not have the money to spend.

[83] *See* 12 C.F.R. § 204.2 (b)(1) (2012) (defining a "demand deposit" as a deposit with a bank that is payable on demand).

In conclusion, when corporations and households turn to financial intermediaries they are, in essence, paying the intermediaries to take over some of the transactional risks due to intertemporal, coordination, strategic, and governance complexity. But as will now see, financial intermediaries and financial systems are themselves subject to similar complexity problems. In order to properly design financial regulations, it is necessary to take into account the extent to which the costs imposed by complex financial institutions and financial products are greater than the benefits created. The first step in this process is to have a better understanding of the complexities involved.

III. Complexity of Financial Systems

This Part analyzes the micro-complexity of financial institutions, financial contracts, and the markets in which they trade, as well as the macro-complexity of the system as a whole.

A. Complexity of Financial Institutions

Modern financial institutions are highly complex organizations.[84] The majority of their assets are financial in nature,[85] which are generally more complex than tangible, physical assets: they are more volatile and their value at any one point is a function

[84] *See* U.S. DEP'T OF TREASURY, *supra* note 13, at 34 (arguing that the complexity of institutions has made it increasingly difficult for regulators to exercise effective oversight).

[85] For example, the assets of commercial banks consist primarily of mortgages and consumer and commercial loans. *See* James Tobin, *Financial Intermediaries*, *in* 2 THE NEW PALGRAVE: A DICTIONARY OF ECONOMICS 340, 342 (John Eatwell et al. eds., 1987) (describing the balance sheets of financial intermediaries as almost completely "paper" on both sides—securities and other financial claims as opposed to real assets—and the assets of commercial banks as comprising primarily mortgages, commercial loans, and consumer credit). The assets of insurance companies are primarily in the form of securities and other financial contracts securities. Richard D. Phillips et al., *Financial Pricing of Insurance in the Multiple-Line Insurance Company*, 65 J. RISK & INS. 597, 602 (1998) (describing the assets of an insurance company as primarily interest and dividend paying securities).

of a large number of potential future states of the world.[86] Also, unlike the customers of standard business firms, the customers of financial institutions hold a large amount of their liabilities; this, in turn, creates special responsibilities on the part of institutions and helps explain why they are subject to a greater level of regulatory oversight. [87] Additionally, financial institutions finance a large part of their operations by borrowing funds from short-term financiers, who can withdraw their funds en masse, with little warning. For example, commercial banks finance their loan portfolios with funds borrowed from depositors and other short-term lenders,[88] and have relatively little equity capital.[89] As a result, compared to other firms,

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[86] *See* Karen Eggleston et al., *The Design and Interpretation of Contracts: Why Complexity Matters*, 95 NW. U. L. REV. 91, 97–100 (2000) (arguing that contractual complexity increases with "(1) the expected number of payoff-relevant contingencies specified in the contract; [and] (2) the variance in the magnitude of the payoffs contracted to flow between the parties," since these create more states of the world for a decision-maker to take into account).

[87] *See* ROBERT C. MERTON, CONTINUOUS-TIME FINANCE 451 (Blackwell Publishers Inc. 2d rev. ed. 1992) (1990) ("[T]he vast bulk of a typical intermediary's liabilities are held by its customers."). In the paradigmatic case, customers make payments over time in return for the institution's promise to do something in the future, such as distribute funds, deliver commodities or securities, or perform some other activity. Moreover, some liabilities, such as insurance contracts, stay in force for long periods, exposing customers to greater risks of default.

[88] *See* FREIXAS & ROCHET, *supra* note 75, at 1 (defining a bank as a firm whose "operation consists in granting loans and receiving deposits from the public"). The Bank Holding Company Act of 1956 defines a "bank" as an "insured bank" under the FDIC Act or any institution organized under Federal or state law which both accepts demand deposits and is in the business of making commercial loans. 12 U.S.C. § 1841(c)(1) (2006). Under the FDIC Act, an "insured bank" is a state or federally chartered bank whose deposits are insured by the FDIC. *Id.* § 1813(a), (h).

[89] *See* TIROLE, *supra* note 60, at 98–9 (stating that banks have high leverage ratios). Banks reduce their intertemporal and coordination risks from making long-term loans by diversifying their depositor base. For example, assume that depositors make deposits in period 0. Short-term depositors will withdraw their funds in period 1 and long-term depositors will do so in period 2. In period 0, the depositors do not know whether they will be short-term or long-term depositors. In period 0, the bank will lend a portion of those deposits to a borrower, who agrees to repay in period 2, at an interest rate that is high enough to reflect the fact it will keep the funds for two

financial institutions are more likely to end up insolvent, with more liabilities than assets, because they have highly leveraged capital structures.[90] This leverage problem is further exacerbated whenever financial institutions have easy access to credit: easy credit allows them to enter into more transactions than if they had to rely on equity or internal financing;[91] this helps magnify both the potential profits and the potential losses.[92]

Moreover, given the volatility of financial markets and the high level of interconnection between financial institutions, the value of an institution's assets and the burden of its liabilities can fluctuate very rapidly, depending on the behavior of markets and other institutions. This is important because a highly leveraged institution can quickly become insolvent if the value or liquidity of its assets is at all compromised,[93] as when, for example, a bank's loan portfolio, traditionally its principal asset, loses value due to increasing defaults by borrowers. Insolvency, in turn, can trigger defaults in credit agreements and can lead to bankruptcy, either in bankruptcy court[94]

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periods. In other words, the borrower is willing to pay a premium for uninterrupted access to those funds. In order to keep the proper reserves to allow for withdrawals in period 1, the bank will need to predict the distribution within its depositor base between long-term and short-term depositors. If a bank fails to accurately predict the number of short-term depositors it has, it will experience a maturity mismatch problem, given that it will not have sufficient reserves to meet the withdrawal demands in period 1.

[90] A firm's leverage is a measure of the extent to which equity-holders rely on other people's money to finance operations. In standard business firms, higher leverage can have the positive effect of helping reduce agency costs. *See* Michael C. Jensen, *Agency Costs of Free Cash Flow, Corporate Finance, and Takeovers*, 76 AM. ECON. REV. 323 (1986) (developing a free cash flow theory in which agency costs are reduced by managers tying their hands with debt payout obligations).

[91] *See* Myers, *supra* note 62, at 581 (discussing pecking order theory).

[92] *See* Nicholas Chan et al., *Do Hedge Funds Increase Systemic Risk?*, 91 FED. RES. BANK ATLANTA ECON. REV., no. 4, 2006, at 49, 50 (stating that leverage helps expand small profit opportunities into large ones, as well as transforming the potential for small losses into larger ones).

[93] *See* ZVI BODIE ET AL., INVESTMENTS 472 (2005) (stating that if a firm's leverage ratio is too high it may be a sign that the firm has taken on too much debt and may be unable to generate enough earnings to pay the principal and interest as it becomes due).

[94] In theory, an insolvent institution can continue to operate until it runs out of cash or other liquid assets to pay its creditors. In practice, however,

or, in the case of insured and systemically important financial institutions, through the resolution authority granted to the FDIC.[95]

Taken together, these characteristics of the assets and liabilities of financial institutions make it more difficult for third parties to fully understand potential asset/liability mismatches, which can lead to insolvency and exacerbate liquidity problems.[96] There are three other factors that increase the complexity of financial institutions. First, institutions are often subject to liabilities that are not reported on their balance sheets;[97] these off-balance sheet liabilities make a financial institution's financial statements less transparent and thus increase the cognitive difficulty of determining an institution's leverage and risk of insolvency. Second, even a healthy financial institution can fail if its customers and investors believe incorrectly that it is facing financial difficulties. For example, a bank run will occur whenever a sufficiently large number of depositors come to believe—either correctly or incorrectly—that the bank is in financial trouble, and may run out of funds before they can withdraw their deposits.[98] Third, financial institutions are comprised of a large number of customers, employees, and investors—whose formal and informal ties are difficult to fully

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creditors may force the insolvent firm into bankruptcy. *See* Clifford W. Smith, Jr., *A Perspective on Accounting-Based Debt Covenant Violations*, 68 ACCT. REV. 289, 292 (1993) (describing role of bargaining failures and debt defaults, including role played by cross-default provisions).

[95] *See* Federal Deposit Insurance Act § 5, 12 U.S.C. § 1815 (2006) (setting forth requirements that financial institutions must meet and procedures they must follow to become and remain FDIC-insured institutions).

[96] In the case of banks, this sort of complexity can affect both the depositors and borrowers. *See* Myron B. Slovin et al., *The Value of Bank Durability: Borrowers as Bank Stakeholders*, 48 J. FIN. 247, 256–57 (1993) (explaining an empirical study finding that the failure of Continental Illinois had a negative effect on the market value of firms with a known borrowing relationship with the bank).

[97] *See* Hyun Song Shin, *Reflections on Northern Rock: The Bank Run That Heralded the Global Financial Crisis*, 23 J. ECON PERSP. 101, 105–08 (2009) (discussing role of off-balance sheet liabilities in the period leading to the Great Recession of 2007–2009).

[98] *See* Douglas W. Diamond & Philip H. Dybvig, *Bank Runs, Deposit Insurance, and Liquidity*, 91 J. POL. ECON. 401, 401 (1983) (defining a bank run as a situation in which "depositors rush to withdraw their deposits because they expect the bank to fail").

discern and create myriad coordination problems.[99]

B. The Complexity of Transactions Involving Financial Institutions

The role of financial intermediaries has changed significantly in recent years, due to the active market for financial innovations.[100] Some of these innovations have allowed financial intermediaries to change the way that they raise funds and hedge risks; others have made it easier for borrowers to get funds directly from investors through market transactions.[101] The aim of some of these financial products is to better allocate risks among parties. However, in doing so, they tend to increase the number of parties involved and the financial interconnections between them.[102] These products also require constant monitoring and re-evaluation of their underlying risks and market value. As financial intermediaries increase the number of these dynamic contractual and financial dependencies, both among themselves and with the business firms and households that are their ultimate customers, they increase the overall complexity of the financial system. In other words, these dynamic dependencies increase the complexity of financial intermediaries and the risk of coordination failures, both of which increase the fragility

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[99] *See* COUNTERPARTY RISK MGMT. POLICY GRP. III, *supra* note 13, at 41 (stating that consolidating financial statements of a parent and its subsidiaries can "obscure those assets and liabilities that are truly impacting the economic performance and financial position of the consolidated enterprise," hide which entity is actually exposed to market risks, and lead to larger, more complex balance sheets that "can obscure individual amounts").

[100] *See* Josh Lerner & Peter Tufano, *The Consequences of Financial Innovation: A Counterfactual Research Agenda*, 3 ANN. REV. FIN ECON. 41, 78 (2011) ("[S]ecuritization was part of a larger set of innovations that constitute the so-called shadow banking system in which market-based financial intermediaries replaced traditional banks.").

[101] Moreover, financial intermediaries, such as investment banks, sometimes act for their own accounts, something that can create conflicts of interests. *See, e.g.*, Dodd-Frank Wall Street Reform and Consumer Protection Act § 619, 12 U.S.C. § 1851 (Supp. V 2011) (restricting the ability of financial institutions to engage in certain types of proprietary trading).

[102] *See* COUNTERPARTY RISK MGMT. POLICY GRP. III, *supra* note 13, at 4 (describing the complexity faced by financial institutions in the day-to-day risk management of portfolios of complex securities).

of intermediaries, as individual entities and as a group. The added complexity also makes it more difficult for regulators to identify and address system-wide risks on a *timely* basis.

These regulatory oversight and risk-management problems are exacerbated as intermediaries compete to develop financial products to exploit new market niches. This in turn leads to the introduction of ever more specialized and complex financial products, which are created on the fly—often by making slight changes to previous securities.[103] Untested and poorly understood financial products can quickly threaten the reliability of existing risk management systems. If these systems are not updated in a timely fashion, they can give managers a false sense of security and lead them to enter into transactions that they would have avoided had they known about the true extent of the risks involved.

Financial products created by combining two or more simpler contracts—or sets of promises—into a more complex one are by nature more difficult to understand and value.[104] To deal with the valuation problem, financial engineers use financial models[105] that are themselves highly complex and difficult to check, both ex ante

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[103] One reason why investment banks may rush to market new financial products is that once a product becomes public other investment banks can copy it and sell it to their own clients. It is much more difficult to get effective intellectual property protection of financial innovations than it is for standard innovations. As a result, the first investment bank to reach the market with a new product will be able to acquire some market share and reputational capital before others copy its innovation. *See* ALLEN & GALE, *supra* note 6, at 45–56. It is, however, possible to get patent protection on some types of financial innovations. *See* State St. Bank & Trust Co. v. Signature Fin. Grp. Inc., 149 F.3d 1368, 1373 (Fed. Cir. 1998) (allowing patents on a financial innovation to consolidate information flow among group of mutual funds), *abrogated by In re* Bilski, 545 F.3d 943, 959–60 (Fed. Cir. 2008).

[104] *See* Sanjeev Arora et al., Computational Complexity and Information Asymmetry in Financial Products 1 (Feb. 5, 2012), *available at* http://www.cs.princeton.edu/~rongge/derivativelatest.pdf (unpublished manuscript) ("The practical downside of derivatives is that they are *complex* assets that are difficult to price.").

[105] Firms, financial intermediaries, and regulators use financial models to make sense of the complex, real-world environment in which financial decisions are made and play out. *See* HO & LEE, *supra* note 6, at 8–9, 546–548 (describing the use of models to value securities, formulate trading strategies, evaluate risk of trading decisions, conduct financial engineering, and evaluate regulated financial companies).

and ex post, to determine whether they are working correctly.[106] In order to test the reliability and robustness of financial models, financial institutions turn to "quantitative experts," who use computer simulations to try to determine how the models' predictions map onto real-world scenarios. One important part of this exercise is to create "stress tests," in which the standard assumptions in a model are replaced with ones involving extreme scenarios.[107] In theory, models that are not sufficiently robust to pass stress tests will be replaced with better ones.[108] But "better" models often require a greater number of assumptions (in order to better reflect real-world environments), which in turn increases their complexity.

C. The Complexity of Financial Systems

First, a definition. A *financial system*, as I will use the term, is comprised of a set of actors who interact through a set of negotiated, "face-to-face" transactions and anonymous market transactions, in the shadow of public and private rules—regulations and contracts. The actors include households, business firms, financial institutions, and regulators. Financial institutions include banks, investment banks, insurance companies, hedge funds, and venture capital and private equity funds. Institutional investors, such

[106] Because financial decisions often involve a large degree of uncertainty about how markets will evolve and unforeseen contingencies that can conflict with the expectations built into a model (in the form of assumptions), an important step in building many financial models is determining what type of probability distribution best captures this uncertainty. Choosing the wrong distribution can reduce the overall reliability of the model. For example, the normal distribution is used in many models because of its tractability, but not all financial uncertainties follow the normal distribution. See *id.* at 26–27 (discussing various contexts in which the normal distribution would lead to the wrong results).

[107] *See* Xin Huang, Hao Zhou & Haibin Zhu, *A Framework for Assessing the Systemic Risk of Major Financial Institutions*, 33 J. BANK. & FIN. 2036, 2037 (2009) (describing role played by stress testing in determining financial health of financial institutions).

[108] One would expect that model designers will sometimes react to these stress test failures not by changing the model, but by changing the test. This is a form of the cognitive dissonance problem documented in the cognitive behavioral literature. *See* LEON FESTINGER, A THEORY OF COGNITIVE DISSONANCE 2–4 (1957) (describing basic mechanisms of cognitive dissonance).

as pension plans, can stand on their own, conceptually, or be included under financial institutions. (For our purposes, the exact characterization does not matter.) Regulators include those charged with regulating financial institutions, as well as regulators of securities and commodities markets. Households, business firms, and financial institutions invest and raise funds from each other. A household can invest in General Motors ("GM") by purchasing shares or debt securities and may finance the purchase of an automobile by borrowing funds from GM. A household may invest in Bank of America ("BofA") by purchasing stock or debt securities, or by opening a demand deposit account; BofA, in turn, may lend funds to the household to finance the purchase of a home. Business firms enter into similar transactions with each other—as when GM purchases a computer system from IBM, agreeing to pay the full amount in sixty days (an account receivable, on IBM's books)—and with financial institutions. Finally, financial institutions invest in each other through equity, standard debt securities, and myriad other sorts of financing arrangements. A financial system's markets include organized exchanges in which equity, debt, and derivative securities are traded; organized exchanges in which commodities and derivative securities related to those commodities are traded; and the "over-the-counter" market—a set of markets in which private transactions take place, often involving financial institutions, institutional investors, and large business firms.

Under the definition of complexity set forth in Part I, a financial system is highly complex, given that it involves a large number of private actors transacting with each other in myriad ways. It also involves a large number of regulators both in the United States and foreign jurisdictions in which U.S financial institutions and business firms transact. The level of complexity increased exponentially with the deregulation of the financial sector and the emergence of the shadow banking system, in which financial institutions and large business firms, such as the financial subsidiaries of automobile manufacturers, engaged in functionally equivalent financial transactions but were subject to different regulatory and disclosure requirements. The shadow banking system both increased the number of actors in the system and made the interconnections between them more opaque.

And as we saw in Part I, complexity increases whenever an observer cannot easily identify the way that two or more components of an environment interact with each other—their interconnections and interdependence. Financial institutions are interconnected to each other directly, through contractual arrangements, such as loan or debt contracts and financial derivatives, and spot transactions, such as trading; and indirectly, through their reliance on the same sources of capital and markets to dispose of assets.[109] The failure of one financial institution can put other institutions at risk,[110] and even relatively small shocks to one part of the financial system can quickly spread to others, precipitating a financial crisis: a large, material change in the overall or aggregate state of a financial system arising from a relatively small change in the system.[111] For example,

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[109] *See* Andrew G. Haldane, Exec. Dir., Fin. Stability, Bank of Eng., Rethinking the Financial Network, Address at the Financial Student Association, Amsterdam 28 (Apr. 2009), *available at* http://www.bankofengland.co.uk/publications/speeches/2009/ speech386.pdf (using a social network approach to model the growing interconnection between institutions).

[110] The likelihood that a financial shock will spill over to other parts of the system is called "systemic risk." *See Hedge Funds, Systemic Risk, and the Financial Crisis of 2007–2008: Hearing Before the H. Comm. on Oversight and Gov't Reform*, 110th Cong. 3–4 (2008) (statement of Andrew Lo) (defining systemic risk as the risk of a "broad-based breakdown in the financial system, often realized as a series of correlated defaults among financial institutions, typically banks, that occurs over a short period of time and typically caused by a single major event"); Steven L. Schwarcz, *Systemic Risk*, 97 GEO. L.J. 193, 204 (2008) (defining systemic risk as the "risk that (i) an economic shock such as market or institutional failure triggers (through a panic or otherwise) either (X) the failure of a chain of markets or institutions or (Y) a chain of significant losses to financial institutions, (ii) resulting in increases in the cost of capital or decreases in its availability, often evidenced by substantial financial-market price volatility").

[111] *See* MARKUS K. BRUNNERMEIER, ASSET PRICING UNDER ASYMMETRIC INFORMATION: BUBBLES, CRASHES, TECHNICAL ANALYSIS, AND HERDING 220 (2001) (describing financial crises that began with small incidents that spread into a system-wide crisis). The mechanism through which shocks get propagated throughout one or more financial systems is referred to as "contagion." *See generally* Marcello Pericoli & Massimo Sbracia, *A Primer on Financial Contagion*, 17 J. ECON. SURVS. 571 (2003) (positing a theoretical framework for financial contagion); IDENTIFYING INTERNATIONAL FINANCIAL CONTAGION: PROGRESS AND CHALLENGES 3–4 (Mardi Dungey & Demosthenos Tambakis eds., 2005) (providing the definition of contagion, but stating that there is broad disagreement in the literature as to the actual parameters of the term); FRANKLIN ALLEN & DOUGLAS GALE, UNDERSTANDING FINANCIAL CRISES 230–31 (2007)

banks routinely lend and borrow from each other, both locally and internationally, a practice aimed at reducing liquidity risks, but one that can also lead to financial crises.[112]

The events leading to the Great Recession of 2007–2009 provide a good illustration of the risks associated with highly complex financial systems. The initial catalyst was the growing awareness of losses in the subprime loan market, which were relatively small compared to subsequent losses in other markets.[113] This subprime shock led to the bursting of the real estate bubble,[114] a crash in the stock market,[115] the freezing up of debt markets,[116] and

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(describing twin crises involving banks and currency markets and summarizing the literature on this topic).

[112] *See* Philippe Aghion et al., *Contagious Bank Failures in a Free Banking System*, 44 EUR. ECON. REV. 713, 715–17 (2000) (developing a global-coordination-failure model of contagion in which the failure of one bank can lead depositors to conclude that failure due to liquidity problems exists in the whole banking system); Franklin Allen & Douglas Gale, *Financial Contagion*, 110 J. POL. ECON. 1 (2000) (developing a model which predicts that interbank markets help decrease the probability of individual bank failure but increase the likelihood of financial contagion); *see also* FREIXAS & ROCHET, *supra* note 75, at 191 (distinguishing between a "bank run" affecting one bank and a "bank panic" affecting the whole banking industry).

[113] *See* Markus K. Brunnermeier, *Deciphering the Liquidity and Credit Crunch 2007–2008*, 23 J. ECON. PERSP. 77, 77 (2009) (describing the losses due to subprime loans as "relatively modest" compared to the losses when the stock market subsequently crashed); Gary Gorton, *Information, Liquidity, and the (Ongoing) Panic of 2007*, 99 AM. ECON. REV. 567, 568 (2009) (arguing that losses in the subprime market were not enough to trigger the crisis until it became "common knowledge" due to introduction of the ABX index, which allowed traders to hedge and speculate vis-à-vis deteriorating portfolios of asset-backed securities).

[114] *See* Gorton, *supra* note 113, at 567–68 (discussing the bursting of the real estate bubble and the contagion effect).

[115] *See* Brunnermeier, *supra* note 113, at 77 (stating that the market crash between October 2007 and October 2008 led to a loss in capitalization of $8 trillion).

[116] *See* Ricardo J. Caballero, *Sudden Financial Arrest* 10–11 (MIT Dep't of Econ. Working Paper No. 09-29, 2009), *available at* http://ssrn.com/abstract=1504985 (discussing the freezing up of credit markets at the beginning of the Great Recession due to a lack of transparency and liquidity hoarding by institutions worried about extent of the growing financial crisis).

the bailout (or failure) of a number of large financial institutions; all of which played out notwithstanding concerted efforts by central banks around the world to contain the crisis.[117]

Finally, in the period leading up to the Great Recession, the complexity of the financial system also increased vis-à-vis one important type of participant: non-expert households, which entered into relatively complex financial transactions. A homeowner who takes out a variable rate second mortgage on her primary home and uses it to purchase a second home, is entering into a complex intertemporal transaction that requires predicting the likelihood that her income stream and interest rates will remain at a certain level.

IV. Managing Complexity: An Engineering Approach

Complexity is not an absolute constraint, but one that can be managed by making adjustments along three dimensions: (1) reducing the number of components in a system; (2) designing an interface that makes the interaction between system components more transparent and reliable;[118] and (3) actively managing who gets to use the system, and designing it in a manner that specifically targets the bounded rationality constraints of particular types of users. When managing complexity, it is important to keep all three dimensions in mind. For example, if one accepts that it would be valuable to reduce the complexity of a set of legal rules, it does not follow that we are committed to reducing the number of rules. One can reduce the overall level of complexity without reducing the number of rules, or even by adding new ones, by making their interaction more transparent and easier to understand. Moreover, reducing the number of rules may increase the overall complexity of the group as a whole, if the remaining ones interact in a manner that is less obvious than before. Engineers have given great attention to developing techniques to better describe, understand, and manage complexity so that they can continue to add additional components to

[117] *See* Anna Gelpern, *Financial Crisis Containment*, 41 CONN. L. REV. 1051, 1058–72 (2008–2009) (setting forth basic challenges faced by regulators trying to contain a financial crisis).

[118] *See* HERBERT A. SIMON, *The Organization of Complex Systems*, *in* MODELS OF DISCOVERY 245, 254 (1977) (stating that loose coupling of system components allows each component to operate independently of others by localizing all interactions on inputs and outputs carried out through the interface of each component).

already complex systems. This Part analyzes some of these engineering techniques available to regulators to design financial regulations and monitor financial systems.

A. Abstraction: Information Hiding and Modular Design

Abstraction is the most common technique used by engineers to manage complexity. Abstractions have to be specifically tailored for the problem at hand and the different actors involved. A doctor, painter, philosopher, and automobile designer will each manage the complexity of the human body using different types of abstractions when they are each at work, and yet use identical ones when standing in front of a mirror at home.[119]

According to the Webster New International Dictionary, *abstraction* is

> 2 a: The act or process of leaving out of consideration one or more qualities of a complex object so as to attend to others (as when the mind considers the form of a tree by itself or the color of the leaves independently of their size or color);
> b: the act or process of imaginatively isolating or considering apart the common properties or characteristics of distinct objects (~ is necessary for the classification of things into genera and species).[120]

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119 *See* ROBIN MILNER, COMMUNICATION AND CONCURRENCY 11 (C.A.R. Hoar ed. 1989) (stating that "we do not treat a person as a network of parts when we are interested in companies, though this treatment is essential for the anatomist").

120 WEBSTER (THIRD) NEW INTERNATIONAL DICTIONARY 8 (Unabridged) (1993); *see* CALEB DRAKE, OBJECT ORIENTED PROGRAMMING WITH C++ AND SMALLTALK 98 (1998) (stating that abstraction is "the process of extracting the relevant information about a category, entity, or activity, and ignoring the inessential details"); ROBERT CECIL MARTIN, DESIGNING OBJECT-ORIENTED C++ APPLICATIONS: USING THE BOOCH METHOD 9 (1995) (stating that abstraction involves the "elimination of the irrelevant and the amplification of the essential").

The first part of the definition describes the top-down-approach to abstraction.[121] Under this approach, the observer is confronted with a complex system and attempts to comprehend it by ignoring some of its parts.[122] In a similar fashion, a designer can help manage complexity by hiding information[123] that it determines is not necessary for a user to interact with a complex system.[124] The second

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[121] People routinely use abstractions to manage every day complexity, often automatically and without conscious choice. For example, our eyes have evolved to filter out irrelevant inputs so that we can focus on what we are looking at. *See* Timothy H. Goldsmith, *Optimization, Constraint, and History in the Evolution of Eyes*, 65 Q. REV. BIOLOGY 281, 282–84 (1990) (describing end result of several evolutionary processes by which eyes have adapted to, among other things, abstract away from superfluous information).

[122] *See, e.g.*, HAROLD ABELSON & GERALD JAY SUSSMAN, STRUCTURE AND INTERPRETATION OF COMPUTER PROGRAMS 80–82 (2d ed. 1996) (describing the use of data abstraction in computer programs in order to clearly separate the way that data objects are *implemented*—the manner in which data is represented and stored in the computer's memory—from the way that they are *used* by procedures that manipulate them).

[123] *See* DRAKE, *supra* note 120, at 101 (describing information hiding as the act of hiding inessential information from the user of a complex object, so that they can be effectively ignored).

[124] For example, the relation between a visitor to a museum and the paintings she encounters will be mediated through a number of compositional devices developed to consciously guide the viewer's eye to specific parts of the painting, in a specific order, and to create the illusion of depth and volume. Brunelleschi's "discovery" of perspective allowed Renaissance painters to create the illusion of three-dimensionality through a set of simple tools. Painters were thus able to reduce the cognitive load faced by a person trying to make sense of a painting. Perspective, in short, made it easier for viewers to comprehend the relationship between the things depicted in a painting; it did so by presenting a viewer with a pre-processed picture of reality, one that mimicked the way that people perceive depth and the relative positioning of objects in the real world. Before Brunelleschi, painters used other more complex techniques for creating the sense of depth, since they required more processing and imagination by the viewer—e.g., picturing a row of angels each standing behind the other. *See* FREDERICK HARTT, HISTORY OF ITALIAN RENAISSANCE ART 161–63 (6th ed. 2007). The same relation holds between a reader and a novel, where a number of well-worn techniques are used to frame the reader's expectations. The novel itself is the interface through which the reader and novelist interact. In post-structuralist approaches to literature and art, the critic is sometimes imposed (or imposes herself) into the mix, as a sort of additional

part of the definition describes a bottom-up approach in which an observer is confronted with a system with a large number of parts, and tackles complexity by categorizing them. Under this approach the observer will look for patterns or commonalities among otherwise disparate parts, and use these to aggregate them into self-contained modules.

1. Information Hiding

Since the cognitive load of interacting with a system increases with the number of components, it follows that "hiding" some of them a designer can reduce complexity.[125] The *state* of a system is a complete description of all truths about it at a particular point in time;[126] information hiding is a way of keeping some of these truths away from an observer. Determining which facts are worthy of attention and which can be ignored is itself a complex task. If one hides too much information, observers may form an incorrect belief about the system's state and make erroneous decisions; on the other hand, if one exposes too much information,

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interface between the creator and audience. Of course, reducing complexity is not always the goal in creative enterprises. Postmodern novelists intentionally disrupt the reader's expectations—for example, of chronological order and consistent point-of-view—which in turn has the effect of increasing the complexity the work. *See* E.W.E.M. Kneepkens & Rolf A. Zwaan, *Emotions and Literary Text Comprehension*, 23 POETICS 125,133–34 (1994) (discussing ways that postmodern novels disrupt a reader's expectations).

[125] *See* STEVE MCCONNELL, CODE COMPLETE 118 (1993) (stating, in the context of software engineering, that information hiding is "one of the few theoretical techniques that has indisputably proven its value in practice"); STEVE SCHNEIDER, CONCURRENT AND REAL-TIME SYSTEMS: THE CSP APPROACH 31 (2000) (describing the principal approach for designing concurrent systems, one in which each system component is modeled as a self-contained entity which hides all information about its current state, except for the information it explicitly shares when it interacts with another through a clearly specified interface); SIMON, *supra* note 118, at 254 (stating that in hierarchical systems one can reduce complexity by having the system components operate "in independence of the detail of the others; only the inputs it requires and the output it produces are relevant for the larger aspects of system behavior").

[126] *See supra* note 50 (describing various ways of modeling the state of a system).

the added computational costs may prevent observers from being able to properly use the system in a timely fashion.

For example, information hiding plays an important role in reducing the cognitive load needed to make sense of and use computers.[127] The basic design principle is to hide almost everything from the user, allowing her to affect her interactions via a small number of highly circumscribed communication channels—e.g., a set of keys, a mouse, and a screen that transforms information into easy to comprehend objects, such as folders.[128] The rest of the computer is a black box that hides the myriad operations occurring inside, right down to the billions of zeros and ones that comprise the most basic information in computers.[129] An "interface" is a set of rules that governs the manner in which an observer can extract information from her environment: on one side of the interface resides the information which will remain hidden from observers; on the other, the information that the designer makes available to any observer who interacts with that environment through that interface. Because of this information-filtering characteristic, interfaces are an important mechanism for hiding information. But to make full use of the power of information hiding and interfaces, it is necessary to introduce a second design principle: modular design.

2. Modular Design

According to Herbert Simon, a pioneer in applying concepts of computer science and engineering to the problem of organizational design, the fact "that many complex systems have a nearly decomposable, hierarchic structure is a major facilitating factor enabling us to understand, describe, and even 'see' such

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[127] There is a whole branch of computer science that deals with the problem of reducing the complexity that humans experience when they interact with computers. For an overview of this literature, see Jakob Nielsen, *Usability Engineering*, *in* THE COMPUTER SCIENCE AND ENGINEERING HANDBOOK 1440, 1440–41 (Allen B. Tucker, Jr. ed., 1997).

[128] For an overview of the development of the desktop and mouse, see STEVEN JOHNSON, INTERFACE CULTURE: HOW NEW TECHNOLOGY TRANSFORMS THE WAY WE CREATE AND COMMUNICATE 42–75 (1997).

[129] As it happens, the "bits" represented by binary code are the smallest chunks into which information can be divided. CHARLES PETZOLD, CODE: THE HIDDEN LANGUAGE OF COMPUTER HARDWARE AND SOFTWARE 70 (2000) (stating that "[a] bit of information is the tiniest amount of information possible").

systems and their parts."[130] Since the complexity is due to both the number of parts of a system and the manner in which they interact, the aim of modular design is to reduce the number of components by bundling them and simplifying their interactions through the use of well-thought-out interfaces.[131] Modular design "glues" together the various components of a complex system[132] in order to (1) reduce the cognitive load faced by both designers and users;[133] (2) make it easier to modify the system by reducing the number of interdependencies among its components;[134] and (3) create "standardized modules" that can be reused when creating new systems with similar functionality.[135]

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[130] SIMON, *supra* note 17, at 207.

[131] *See* ABELSON & SUSSMAN, *supra* note 122, at 359 (stating that computer programmers control complexity using same type of modularity techniques used by engineers at large, in which the system is stratified along different levels of abstraction, "each one adopting appropriate large-scale views of system structure").

[132] Systems may be divided into modules along a number of dimensions—e.g., according to common functionality, types of information or data, or even by grouping functionality with the information needed to carry out the actions in question. For a discussion of these different approaches, see MCCONNELL, *supra* note 125, at 159–60 (providing rules-of-thumb for choosing between functional, data-abstraction, and object-oriented approaches).

[133] *See* ABELSON & SUSSMAN, *supra* note 122, at 140–141 (stating that stratified modular design, where each strata is a module encapsulating horizontally related modules, helps reduce complexity by making programs more robust, given that it increases the likelihood that "small changes in a specification will require correspondingly small changes in the program").

[134] *See* MARTIN, *supra* note 120, at 108 (stating that modularity allows designers to change the information and functionality hidden within a module without having a rippling effect through the rest of the system; that is, they are able to change the internal of one module without having to change those of other modules; all that they need to do to assure that the system continues to work properly is to make the requisite changes on the interfaces of each of those modules); MCCONNELL, *supra* note 125, at 123–24 (arguing that modularity allows system designers to isolate unstable areas that are likely to change).

[135] *See* BERTRAND MEYER, OBJECT-ORIENTED SOFTWARE CONSTRUCTION 68–74 (2d ed. 1997) (stating that the benefits of module reusability include reducing the time needed to design, implement, and test new systems, and identifying common patterns that can be reused for solving analogous problems); *see also* CHRISTOPHER ALEXANDER ET AL., A PATTERN

The design process involves two steps. First, a designer will group together the parts of the system that are closely related—e.g., those that use the same information or undertake related tasks. The goal in this first step is to encapsulate these related items into self-contained, *cohesive* modules.[136] A module is self-contained in the sense that its components will be able to freely interact with each other, but everyone else transacting with it will have to do so through the module's interface.[137] A module is thus a way to apply the concept of information hiding to collections of system components. For example, if module *A* needs information from module *B*, it will only be able to acquire information made public on *B*'s interface; and it will be able to do so only if its own interface is able to receive it—i.e. observe that type of information. Similarly, if *A* wants *B* to undertake some action, it will be limited to those that are made available on *B*'s interface; and the consequences of *B*'s actions will be transmitted through their respective interfaces.[138]

Not surprisingly, the second step of the modular design process involves specifying the extent to which different modules will be able to interact with each other and determining the timing of those interactions. In this step, the goal is to reduce, as much as

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LANGUAGE x (1977) (describing the use of pattern languages within architecture, in which each pattern describes a recurring type of problem across various domains and known solutions that can be adapted and reused); ERICH GAMMA ET AL., DESIGN PATTERNS: ELEMENTS OF REUSABLE OBJECT-ORIENTED SOFTWARE 356–58 (1995) (extending pattern language concept to the area of software design).

[136] *See* DRAKE, *supra* note 120, at 108 (stating that "cohesion describes the degree of connectedness among the elements encapsulate within a module").

[137] A module may of course be composed of other modules, which interact with each other through clearly defined interfaces. As Herbert Simon pointed out, hierarchies are useful in managing complexity because they provide a way to hide parts of the system in a manner analogous to a set of Chinese boxes—i.e., a box enclosing another box, which in turn encloses another, and so on. *See generally* SIMON, *supra* note 118, at 246 (stating that when one opens one of these boxes, one "discloses not just a new box within, but a whole set of boxes").

[138] The idea is that a module should be able to interact with another without having to know the private information encapsulated within it. *See, e.g.*, MARTIN, *supra* note 120, at 9 (stating that in a properly modularized system "[n]othing can be done to a module unless it is done through its interface"—i.e., the interface acts as a set of control made available to other modules who want to affect its behavior).

possible, the coupling or interdependencies between modules—i.e., the extent in which they require the cooperation of others to accomplish their own individual goals. For example, object-oriented computer languages bundle together, within "objects," data and the procedures used for manipulating it; everything is encapsulated, except for a small portion that is exposed on each object's interface to allow them to communicate with each other.[139] Object-oriented design, therefore, makes use of both modularity and information hiding.

B. Domain-Specific Languages

At their core, languages are nothing more than a set of rules for managing complexity. [140] For example, the language of first-order logic provides a set of primitives and ways of combining them into

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[139] Computer scientists have developed a number of programming languages with the specific aim of reducing the complexity faced by programmers. Pure object-oriented languages accomplish this by requiring that all interactions between system components occur by exchanging messages through clearly specified interfaces. The first ones to exploit this technique include CLU and Smalltalk, and computer scientists' efforts eventually led to the development of a number of object-oriented languages, such as C++ and Java. For a history of these developments, see RAPHAEL A. FINKEL, ADVANCED PROGRAMMING LANGUAGE DESIGN 139–167 (1996) (discussing object-oriented languages).

[140] Not all languages are used for communication. It is possible for someone to have their own private language that they use to organize their thoughts and reduce the cognitive load of making decisions. *See* ABELSON & SUSSMAN, *supra* note 122, at 4 (arguing that languages are a way of combining simple ideas to form more complex ones that can be manipulated as a unit, including combining them with other complex ideas). A person may always translate her private language to one that can be used to communicate with a third party, or can teach it to him. There is another use of the term private language—a language that captures all of the private or internal thoughts and sensations of its users. Whether this is possible was called into question by Wittgenstein. *See* LUDWIG WITTGENSTEIN, PHILOSOPHICAL INVESTIGATIONS §§ 243–315 (G. E. M. Anscombe trans., 1953) (discussing private and non-private languages in the context of sensations, pain, and expressions); *see also* SAUL A. KRIPKE, WITTGENSTEIN ON RULES AND PRIVATE LANGUAGE 55–113 (1982) (analyzing the "private language" argument presented in Wittgenstein's *Philosophical Investigations*).

more complex, well-formed logical structures.[141] The English language provides a set of rules for combining letters into words and attaching meaning to those words, as well as a set of rules for combining words into syntactically correct sentences. In a similar fashion, a high-level computer language allows a programmer to structure programs in a more transparent, less complex manner, which makes it easier to implement, test, and update them.[142]

One approach used by engineers to deal with complexity is to establish new languages.[143] In many cases, these are not full-fledged languages, but smaller ones that are embedded within existing languages.[144] These are known as domain-specific languages

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[141] A formal model will be used to interpret logical constructs—i.e., to attach meanings to both primitive and compound formulas. A formula is a compound object formed from the primitives of that language; both the primitives and formulas are attached a truth value—either true or false—and a model of a formula is an interpretation for which that formula comes out true. *See* GEOFFREY HUNTER, METALOGIC: AN INTRODUCTION TO THE METATHEORY OF STANDARD FIRST ORDER LOGIC 4–15 (1971) ("A *model* of a formula of a language is an interpretation of the language for which the formula comes out true.").

[142] *See* DRAKE, *supra* note 120, at 97–136 (discussing use of higher-level languages to reduce complexity).

[143] According to the MIT computer scientists Abelson and Sussman:

> Establishing new languages is a powerful strategy for controlling complexity in engineering design; we can often enhance our ability to deal with a complex problem by adopting a new language that enables us to describe (and hence think about) the problem in a different way, using primitives, means of combination, and means of abstraction that are particularly well suited to the problem at hand. . . . The same idea is pervasive throughout engineering.

ABELSON & SUSSMAN, *supra* note 122, at 359 & n.1; *see also* SHRIRAM KRISHNAMURTHI, PROGRAMMING LANGUAGES: APPLICATION AND INTERPRETATION 315 (2003) (stating that "languages are *abstractions*: ways of seeing or organizing the world according to certain patterns, so that a task becomes easier to carry out" (emphasis in original)).

[144] This is yet another example of modular design—in this case of a language. A language designer has to provide not just a list of primitives and rules for combining these into more complex language constructs, but also a model or interpreter that will process well-formed language constructs (i.e., those formed in accordance to the syntactical rules). It is through this evaluation process that meanings are attached to language

because they are tailored for handling the complexity that is specific to a particular domain or environment.[145] Since a language is an abstract model or representation of reality, processing the same stream of data using two different languages can lead to different conclusions.[146] Different languages, in short, allow individuals to talk and think about the same problem in different ways.[147]

C. Scripts

The theory of scripts was developed by computer scientists to help design intelligent artificial agents; a script is a "set of expectations about what will happen next in a well-understood situation."[148] As such, they encapsulate memory and knowledge in order to make our mental processing easier and allow us to draw

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constructs, using semantic functions that are instantiated though the model or interpreter. One way to modularize languages is to create a base language that can be used to create new interpreters for new specialized mini-languages. *See* ABELSON & SUSSMAN, *supra* note 122, at 360 (describing the process of creating new computer languages by creating interpreters that are constructed by using an existing language).

145 *See, e.g.*, PAUL HUDAK, THE HASKELL SCHOOL OF EXPRESSION: LEARNING FUNCTIONAL PROGRAMMING THROUGH MULTIMEDIA 304–12 (2000) (discussing a domain-specific programming language—developed to help musicians compose music—which is in turn embedded within an existing language).

146 *See* ABELSON & SUSSMAN, *supra* note 122, at 359 n.1 (providing an example of circuits, which engineers represent and model using the languages of networks and systems, each of which picks out different aspects of the problem). According to the linguist Whorf, the language used by a person to describe her environment will influence how she structures and interprets her observation. *See* BENJAMIN WHORF, LANGUAGE, THOUGHT, AND REALITY 207–14 (1956) (discussing theory that languages influence the way people interpret reality is relative to the language used to represent it).

147 *See* ABELSON & SUSSMAN, *supra* note 122, at 359 n.1.

148 ROGER C. SCHANK, TELL ME A STORY: A NEW LOOK AT REAL AND ARTIFICIAL MEMORY 7 (1990). Schank draws a comparison between the script of a play or movie and the notions of script as he is using it: "In a sense, many situations in life have the people who participate in them seemingly reading their roles in a play."). *Id.*; *see also* SCHANK & ABELSON, *supra* note 36, at 36–68 (offering a detailed analysis of the role of scripts).

inferences quickly and efficiently.[149] A script, therefore, helps decision-makers deal with their bounded rationality by providing them with an easily accessible repository of information and knowledge; it tells them the sequence of actions that they must take to achieve a goal in a well-understood scenario. For example, the "restaurant script" tells an actor that, when in a restaurant, she should expect to receive a menu from which she will order dinner.[150] Scripts also help actors reduce coordination complexity: they provide them with knowledge of "how to act and how others will act in given stereotypical situations."[151] At the same time, the level of coordination and strategic complexity will increase to the extent that actors use different scripts.[152] This last problem is exacerbated by the fact that scripts are not static, but will change over time to deal with new contingencies or new environments.[153]

V. Real-Time Financial Systems: An Engineering Approach

This Part begins by discussing three critical timing issues in financial system. It then analyzes the relationship between complexity, bounded rationality, and transparency. It continues by

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[149] *See* Richard Nisbett & Lee Ross, *Judgment Heuristics and Knowledge Structures*, *in* NATURALIZING EPISTEMOLOGY 189, 200 (Hilary Kornblith ed., 1985) (describing scripts as an encapsulation of knowledge, so that it can be easily retrieved and used to draw inferences).

[150] *See* SCHANK & ABELSON, *supra* note 36, at 38–42 (describing the "restaurant script," of which the one above is a variation, to illustrate the usefulness of scripts in organizing prior knowledge).

[151] SCHANK, *supra* note 148, at 7 ("Life experience means quite often knowing how to act and how others will act in given stereotypical situations.").

[152] *See, e.g.*, Nisbett & Ross, *supra* note 149, at 206 (arguing that one of the potential costs associated with scripts is "the possibility of erroneous interpretations, inaccurate expectations, and inflexible modes of response").

[153] Scripts bear some resemblance to Nelson & Winter's use of the term *routine*, which they define as "all regular and predictable behavioral patterns of firms," although routines are to be understood against an evolutionary background, playing "the role that genes play in evolutionary theory." *See* RICHARD R. NELSON & SIDNEY G. WINTER, AN EVOLUTIONARY THEORY OF ECONOMIC CHANGE 14 (1982) ("Our general term for all regular and predictable behavioral patterns of firms is 'routine.' . . . In our evolutionary theory, these routines play the role that genes play in evolutionary theory.").

arguing that financial systems are best characterized as safety-critical, real-time systems similar to other complex systems that engineers deal with all the time, such as nuclear power plants and air-traffic control systems. With this in mind, the Part introduces some of the techniques used by engineers to design, implement, and monitor real-time systems. It then discusses two general tradeoffs that system designers need to deal with—that between accuracy and usability, and that between generality and specificity. The last section introduces the concept of "lazy evaluation" used in certain computer languages and shows how it can be used to deal with the complexity of corporate disclosures.

A. Three Timing Issues in Financial Systems

All other things being equal, the more complex a financial institution, the greater the informational asymmetry faced by investors, counterparties, and regulators. Complexity makes it more difficult for outsiders to know how much private information is in the hand of insiders and how to decipher that information once it is revealed to them;[154] it also increases the difficulty of determining the financial health of an institution and the risks posed by its interconnection with other institutions or dependence on particular types of financing arrangements.[155] Resolving these informational problems in a timely fashion becomes paramount in this context given the relative fragility of financial institutions and financial systems: investors, counterparties, and regulators, in short, have to pierce through complexity before a financial crisis is at hand. This section analyzes three timing decisions that will affect the level of real-time transparency in financial systems.

The first is the decision by managers of financial institutions of when to disclose to regulators and their other constituencies that they are experiencing financial difficulties. These other constituencies include shareholders, debtholders, employees, and

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[154] *See* Edward L. Glaeser & Hedi D. Kallal, *Thin Markets, Asymmetric Information, and Mortgage-Backed Securities*, 6 J. FIN. INTERMEDIATION 64, at 64–65 (explaining that within mortgage backed securities markets the sellers of assets have significant informational advantages).

[155] *See, e.g.*, Steven L. Schwarcz, *Regulating Complexity in Financial Markets*, 87 WASH. U. L. REV. 211, 235 (2009) (describing the general "inability of market participants to know how much contingent exposure another participant might have on [dervitatives contracts]").

customers of financial institutions, all of whom are involved in some way in monitoring managers (collectively, "private monitors"). Sometimes increasing disclosure about other parties in a transaction can lead to greater strategic behavior if that information can be used to get a better sense of how the other parties are expected to act. This sort of "over-disclosure" problem has been analyzed in great detail in the mechanism design literature. If there is a group of parties interacting with each other through a mediator, and the mediator provides each party only the information necessary to decide how to act, then it is more likely that each party will disclose all relevant information to the mediator. This is important since the mediator will be able to make a better decision for the group as a whole if the parties have each made truthful revelations.[156]

The second set of timing issues involves the decisions by financial regulators and private monitors of *when* to monitor managers and financial institutions—and when to hold them accountable. As we saw in Part I, the level of complexity depends on the environment and the identity of the observer;[157] it also depends, however, on the timing of those observations. From the perspective of a regulator, the relevant environment includes the financial institution in question, other institutions interconnected with it, their investors and counterparties, and financial markets generally. A private monitor's environment includes each of these actors[158] and financial regulators. Of course, at any one point the environment relevant to a particular monitor may include a smaller subset of these actors. Since an environment will change over time, a monitor will have to determine when to gather information about it.[159] The

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[156] *See* LEONID HURWICZ & STANLEY REITER, DESIGNING ECONOMIC MECHANISMS 29–30 (2002) (describing the privacy preserving assumption, in which an actor makes a decision solely based on her private information); Paul R. Milgrom & Robert J. Weber, *A Theory of Auctions and Competitive Bidding*, 50 ECONOMETRICA 1089, 1090 (1982) (stating that a standard assumption in auction literature is the that each actor will rely solely on private information about its own type); Roger B. Myerson, *Mechanism Design*, *in* THE NEW PALGRAVE: ALLOCATION, INFORMATION, AND MARKETS 191 (John Eatwell et. al eds., 1987) (stating that the "more information that an individual has, the harder it may be to prevent him from gaining by disobeying the mediator").

[157] *See supra* Part I.A.

[158] Excluding itself.

[159] Suppose that a monitor observes the environment at time t, intending to make a decision at time $t + 1$, and to act (if necessary) at $t + 2$. The monitor

monitor will also need to anticipate the extent to which its own behavior can cause the environment to change and how such a change may affect its future welfare. Even if the environment remains unchanged, the monitor itself may change over time. Finally, some environments are more dynamic, or change at a quicker pace, than others do. The more volatile the environment, the greater its complexity—since a monitor will need to take into account a larger number of potential contingencies—and the higher the information costs involved, given that an actor cannot rely on previous observations without at least verifying whether the information in its possession has become stale.[160] We will return to this issue in the next two sections.

The third timing problem involves the decisions by regulators concerning when and how to test existing legal regulations to determine whether they are working well; even when regulatory shortcomings are identified, these same regulators have to determine when to make the requisite changes. The latter includes a regulator's decision of when to disclose to Congress and courts that they need to act. This third timing issue is of particular importance in the regulation of modern financial institutions, given the speed with which market players are able to create new types of securities and institutional frameworks, both to better allocate risks and escape legal oversight.[161] It is not just regulators who have to test their rules

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will need to take into account the likelihood that the environment may change between each of these intervals. Moreover, to the extent that an action requires time to complete—from t +2 to t + 3—the monitor will also need to account for possibility that the relevant aspects of the environment will change during the execution phase.

[160] In some cases, the information will become stale before it can be processed and used. *See* Ben Kao et al., *Updates and View Maintenance in Soft Real-Time Database Systems*, 8 INT'L CONF. INFO. & KNOWLEDGE MGMT. 300, 300–01 (1999) (distinguishing between transaction timeliness—how fast system carries out a requested transaction—and data timeliness—the relative freshness or staleness of data).

[161] This is due to the fact that modern financial models make it relatively easy to design and value ever more complex financial contracts, and to avoid existing regulations by designing institutions and transactions that are functionally equivalent to regulated ones, but which fall within a regulatory loophole. *See* Frank Partnoy, *Financial Derivatives and the Cost of Regulatory Arbitrage*, 22 J. CORP. L. 211, 256 (1997) (explaining how analysis and economic models outline "the circumstances under which a particular type of financial derivatives regulation would be worthwhile, i.e.,

intermittently to determine whether they are meeting their stated goal. Parties to financial contracts face a similar problem. Over time, contracts will become standardized, and parties will adopt them without making material changes. Standardization is valuable since it helps reduce the transaction costs of bargaining over specific provisions; but standard contracts can, over time, become stale or malfunction, in the same manner that equipment using outdated technology may misfire.

B. The Relationship Between Complexity and Transparency

Transparency refers to a decision-maker's level of access to information about her environment.[162] Given the bounded rationality of actors, however, what really matters is having access to the relevant information before they have to commit to a course of action.[163] It follows that what is ultimately important is a decision-maker's ability to acquire, process, and use relevant information about the environment in a timely fashion. A decision-maker starts with a goal, a set of beliefs, and a set of feasible actions that can help her achieve that goal. Among other things, she holds beliefs about certain aspects or properties of her environment, including its current state and way it may evolve. Suppose that the true state of the environment (or its expected state in the future) is defined by a set of properties (*x*, *y*, *z*, etc.); that environment is transparent if the decision-maker believes that all of these properties are true. The level

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efficient, and . . . suggest, based on the various motivations for derivatives transacting, why certain existing and proposed attempts at regulation are futile").

[162] An environment is accessible to the extent that an agent is able to ascertain its actual state by merely observing it. *See* STUART J. RUSSELL & PETER NORVIG, ARTIFICIAL INTELLIGENCE: A MODERN APPROACH 46 (3d ed. 2009) (drawing distinction between accessible environments, in which an agent is able to ascertain the true state of an environment by observing it, and non-accessible ones, in which observation provides only partial information of an environment's true state).

[163] *See* FIN. ACCOUNTING STANDARDS BD., STATEMENT OF FINANCIAL ACCOUNTING CONCEPTS NO. 2. ¶ 56, at 2–17 (2008), *available at* http://www.fasb.org/cs/BlobServer?blobkey=id&blobwhere=1175820900526&blobheader=application%2Fpdf&blobcol=urldata&blobtable=MungoBlobs (stating that information is timely if it is available to users "before it loses its capacity to influence decisions").

of transparency will go down to the extent that the observer is mistaken about one or more of them.[164] The environment is transparent in real-time if the decision-maker comes to hold true beliefs about the relevant properties, while she still has the ability to change her mind about a planned course of action.[165] An environment is completely opaque if the decision-maker does not hold any true beliefs about any of its relevant properties at the time of acting. Finally, real-time transparency and opaqueness lie in a continuum: at one end is complete real-time transparency, in which a decision-maker has access in real time to all of the information that she needs to make a fully informed decision; at the other end of the spectrum is complete opacity, in which the actor makes the decision completely blind—i.e., without access to any relevant information.

C. Financial Systems as Real-Time, Safety-Critical Systems

A financial system is a safety-critical, real-time system. A real-time system is one whose behavior is judged not just on whether the operations that it performs yield the correct or desired result, but

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[164] All other things being equal, the greater the amount of information needed to create transparency, the greater the complexity. However, not all properties will be equally important for the decision at hand, so one must further specify the level of importance of each property as well as combinations of them.

[165] Real-time transparency plays an important role in capital markets. *See, e.g.*, MAUREEN O'HARA, MARKET MICROSTRUCTURE THEORY 252–60 (1995) (discussing various issues in defining market transparency in the context of capital markets); Securities Exchange Act of 1934 § 11A(a)(1)(C), 15 U.S.C. § 78k-1(a)(1)(C) (2006) (proclaiming that fair and orderly markets require that information is made available to brokers, dealers, and investors); DIV. OF MKT. REG., U.S. SEC. & EXCH. COMM'N, MARKET 2000: AN EXAMINATION OF CURRENT EQUITY MARKET DEVELOPMENTS 17 (1994) ("Transparency [in the capital markets] refers to the real-time dissemination of information about prices, volume, and trades."); DIV. OF MKT. REG., U.S. SEC. & EXCH. COMM'N, ADVISORY COMMITTEE ON MARKET INFORMATION: MINUTES OF OCTOBER 10, 2000 MEETING (2000), *available at* http://www.sec.gov/divisions/marketreg/marketinfo/101000mtg.htm ("[R]eal-time public dissemination of trade and quotation information is one of the central components of our national market system.").

also on whether they are completed on time;[166] examples include air traffic controller systems, command and control systems used by the military, nuclear power plants, and mobile and wireless computing.[167] In an ideal world, the monitor of a real-time system will acquire and process all of the information needed to make an accurate decision.[168] The costs of making a decision will thus involve the costs of acquiring and processing the relevant information, including the time and effort needed to transform it into a format that can be used to make a decision.

When a monitor interacts with safety-critical, real-time systems, it needs to have information that is valid or fresh.[169] An air traffic controller needs to have fresh data about the position of the different planes under her control. Delays in updating this data can lead to catastrophic results.[170] The same is true with other types of

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[166] *See* John A. Stankovic, *Real-Time and Embedded Systems*, *in* THE COMPUTER SCIENCE AND ENGINEERING HANDBOOK, *supra* note 127, at 1709 (stating that a real-time system is one in which the correctness of the system depends on both the logical result of the computation and the time in which the results are produced).

[167] *See id.*

[168] As a general matter, a "fully accurate" decision is one the decision-maker would not change if she had additional information. *See* John W. Payne & James R. Bettman, *Preferential Choice and Adaptive Strategy Use*, *in* BOUNDED RATIONALITY: THE ADAPTIVE TOOLBOX, 123, 133–34 (G. Gigerenzer & R. Selten eds., 2001) (discussing various metrics used in the rationality literature to assess the "accuracy" of decisions).

[169] *See* Stuart Anderson & Juliana Kuster Filipe, *Guaranteeing Temporal Validity with a Real-Time Logic of Knowledge*, *in* IEEE COMPUTER SOC'Y, PROCEEDINGS OF THE 23RD INTERNATIONAL CONFERENCE ON DISTRIBUTED COMPUTING SYSTEMS 178, 178 (2003) ("The older the data gets the more unusable and unreliable it becomes."); Ben Kao et al., *Updates and View Maintenance in Soft Real-Time Database Systems*, *in* ASS'N FOR COMPUTING MACH., PROCEEDINGS OF THE EIGHTH INTERNATIONAL CONFERENCE ON INFORMATION AND KNOWLEDGE MANAGEMENT 300, 303 (1999) (describing situations in which, in order to make right decision, an actor has to use fresh data that faithfully reflects the current state of the environment).

[170] These are referred to as "hard" real-time systems in the sense that, if information is received past the set deadline, it loses all of its value. *See* Albert Benveniste & Gerard Berry, *The Synchronous Approach to Reactive and Real-Time Systems*, 79 PROCEEDINGS IEEE 1270, 1270 (1991) (a logically correct real-time program may produce catastrophic results if outputs are not produced in time).

safety-critical systems, such as nuclear power plants, transportation systems, and medical equipment.[171] Stale information can, for example, exacerbate herding behavior within financial systems; bank runs occur when some depositors believe that they have stale information about the current financial state of banks, but believe that other depositors have fresher, more accurate information.[172] While it is usually assumed that the older the data, the less useful it is, this is not always the case. In some scenarios, the longer a piece of data survives without being replaced, the greater its validity.[173]

More generally, a monitoring event occurs in "real time" if it is carried out within a specified deadline.[174] In setting these deadlines

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[171] In other cases, the time constraint is not critical, but a failure to meet that constraint leads to a decrease in the value of the data. *See* Martin Torngren, *Fundamentals of Implementing Real-Time Control Applications in Distributed Computer Systems*, 14 REAL-TIME SYS. 219, 222 (1998) (stating that systems may have different "timing tolerances"—that is, costs or sensitivities associated with a deviation from the stated deadline).

[172] It is possible that the same piece of information has more than one temporal validity interval, depending on the party using the information. *See generally* Alan Burns et al., Modeling Temporal Behaviour in Complex Socio-Technical Systems, Technical Report YCS-2005-390 (2005) (unpublished manuscript), *available at* ftp://ftp.cs.york.ac.uk/reports/2005/YCS/390/YCS-2005-390.pdf (developing a model of complex social systems in which there are multiple "time bands," each one applicable to a different view or perspective of the system); Anderson & Filipe, *supra* note 169, at 179 (distinguishing between temporal consistency "at all times" and within "local time frames").

[173] *See* Stankovic, *supra* note 166, at 1711 (arguing that a common mistake in designing real-time systems is adopting a blanket assumption that timely disclosure is critical in all contexts).

[174] An event is something that happens within a system, an "event occurrence" is the point in time in which a particular event occurs within a system, and a timing safety constraint is a relation between event occurrences. For example, if *E* is the start of task and *E** the end, then a timing constraint, such as a deadline, is a relation between *E* and *E**. *See* Farnam Jahanian et al., *Runtime Monitoring of Timing Constraints in Distributed Real-Time Systems*, 7 REAL-TIME SYS. 247, 251 (1994) ("Informally, events represent things that happen in a system. For example, an event may denote the start/completion of a program segment, reading a new sensor value into a program variable or receiving a message from another task. An event occurrence defines a point in time at which a particular instance of the event happens in a computation. Thus, a *safety*, property or a timing constraint can be expressed as an assertion about the

it is important to have a way of identifying and measuring the costs associated with a delay in making a decision. Acting too soon can be as costly as acting too late.[175] The first step in defining a real-time constraint is determining the benefits and costs associated with each delay in making a decision. The second step is identifying a cut-off point or deadline after which waiting produces a net loss, including determining whether the deadline is hard or soft: if a hard deadline is missed, a piece of information loses all of its value and using it may be counterproductive; on the other hand, missing a soft deadline leads to only a partial loss in value of the information in question.[176]

For example, a disclosure by a manager to shareholders or regulators is said to occur in real time,[177] if it occurs before the information is stale. All things being equal, one would expect that monitoring and disclosures will occur more frequently in highly dynamic environments like those in financial markets; at the same time, these environments make it difficult to solely rely on pre-specified monitoring/accountability deadlines. In addition to static deadlines, it is necessary to have a way to identify triggering events that will call for unplanned monitoring or for changes in the existing monitoring schedule.

D. The Tradeoff Between Accuracy and Usability

The act of compressing complex objects to make them theoretically and cognitively manageable is not a lossless translation.

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relationship between event occurrences in a computation." (emphasis in original)).

[175] Sometimes it is necessary to delay a transaction until the information being used by the decision-maker is updated. That is, there is a positive option value to delaying the transaction until some of the uncertainty has been resolved by the arrival of new information. *See* Ming Xiong et al., *Scheduling Transactions with Temporal Constraints: Exploiting Data Semantics*, 17 REAL-TIME SYS. 240, 243 (1996) (describing real-time systems in which an actor cannot enter a transaction until information is updated).

[176] *See* Stankovic, *supra* note 166, at 1709 (drawing a distinction between hard and soft real-time systems; in the former case, information that is not acquired by specified deadline loses all its value, while in the soft system information depreciates in value).

[177] While commentators and regulators routinely make reference to "timely" disclosures, they do not always indicate how one would go about determining whether a specific disclosure is timely.

The person who transforms them into abstract, well ordered realities will necessarily make choices, often implicitly, about the types of information that can be "safely" ignored. A system designer, therefore, has to determine the proper tradeoff between the accuracy and usability of information. If the system is a nuclear power plant, it is important to get an accurate reading of the temperature inside the reactor's core; at the same time, greater accuracy will require more data and thus more computational resources and processing time. What ultimately matters is getting an accurate reading in a timely fashion. One way that designers have dealt with this type of problem is by taking measurements at set intervals, and if those measurements indicate that there is a potential problem, dynamically taking more extensive, "accurate" measurements. During the time that the more detailed measurements are being made and processed, the plant's operator may determine, given other threshold signals, that the reactor has to be shut down immediately—i.e., before getting a full, accurate reading.[178]

E. The Tradeoff Between Generality and Specificity

As we have seen, in order to manage complexity, a system designer will have to tailor her design to take into account not just the problem that the system is trying to solve but also the type of users—their identity and characteristics—and the timing of their interactions with the system. One approach is to draw few distinctions between different users and use an abstraction that will reduce the overall complexity, on average. The same holds for the timing of interactions, where what ultimately matters is whether or not the observers remain invariant over time—i.e., the user is using the object for the same purpose, perceiving it in the same way, and experiencing the same level of cognitive load when interacting with it. While such a course of abstraction is sometimes warranted, in some cases a designer may need to partition the set of users into a larger number of subsets and create a different "view" for each of these. (The same holds for different time periods.) Each view creates an abstraction barrier that is tailored to the particular users. While

[178] For a discussion of the multiple-tier safety procedures, see Stankovic, *supra* note 166, 1710–11 (reviewing the concepts of sensors, time correctness, timing constraints, and critical tasks in the context of real-time systems using examples of safety procedures for nuclear reactors, aircraft control, and automated factory floors).

creating different abstractions for different users can increase the complexity at the time of designing a system, the increased cost from that added complexity needs to be weighed against the benefits of reducing the level of complexity during the operation of the system.

F. Sequential Disclosures and "Lazy Evaluation" of Information

One approach for dealing with complexity is to release information incrementally, as opposed to doing so in one bulk disclosure. In other words one way of reducing the cognitive load of processing information is to process it sequentially.[179] This is, of course, feasible only in cases in which there are no real-time constraints. A second related approach is to release all of the information at once and set up a mechanism so that actors process information only when they need it. This approach, referred to as "lazy evaluation," plays an important role in some high-level programming languages, such as Haskell. The basic idea is to evaluate functions only when it is clear that the program needs the information to continue to execute properly.[180] A program that uses lazy evaluation can process infinite lists in finite time, given that such lists would not be evaluated until they are needed (and only those portions that are relevant to the task at hand). Lazy evaluation, therefore, allows programmers to create the illusion that a list of objects is infinite when in fact it is not.

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[179] It is not necessary for the whole information bundle to be completely processed before an actor can undertake other processing tasks. The only requirement is that the actor can eventually reconstitute the knowledge gained from processing each chunk. For example, operating systems are designed so that they can interrupt an ongoing process to take on a new one with higher priority, and to be able to return to the interrupted process in some future period to continue its execution. *See* Thomas E. Anderson et al., *Thread Management for Shared-Memory Multiprocessors*, *in* THE COMPUTER SCIENCE AND ENGINEERING HANDBOOK, *supra* note 127, at 1165, 1670–72 (describing processor scheduling issues in operating systems).

[180] *See generally* RICHARD BIRD, INTRODUCTION TO FUNCTIONAL PROGRAMMING USING HASKELL 217–221 (2d ed. 1998) (describing how lazy evaluations helps reduce two types of complexity problems in computer programs: those brought about by the limited storage space within computers and the limited time to execute programs).

VI. Conclusion

Complexity can lead actors to make sub-optimal decisions. It can also lead them to delay discovering the error of their ways and taking corrective actions. This persistence of bad decisions can, in turn, have a spillover effect: it can affect the types of goals that actors choose in future periods and the way that they go about pursuing them. The general problem is only exacerbated when individuals are embedded within social contexts in which their actions affect others and where they must try to predict how others will act in pursuing their own goals. With this in mind, this Article has provided an analysis of the complexity of financial systems and of the problem of identifying and dealing with the deteriorating health of financial institutions, in real time. The Article expands our general understanding of complexity by introducing the concepts of intertemporal, coordination, strategic, and governance complexity. The Article, in addition, identifies and develops the implications of the relationship between complexity and real-time constraints, and discusses various types of mechanisms used by engineers when designing, implementing, and testing complex systems, generally, and safety-critical, real-time systems, in particular. The aim of the Article therefore is to further our understanding of financial systems and of the tools available to regulators when designing financial regulations.