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Modularity after the Crash

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Prepared for *Managing the Modular Age: Architectures, Networks And Organizations*, edited by Raghu Garud, Arun Kumaraswamy and Richard Langlois, Blackwell Publishers, Oxford, UK. Contributors to this volume were asked to comment on an earlier work, "extending the original arguments…[and] reflecting on how the ideas are applicable to the new Internet economy." The volume will be dedicated to the memory of Herbert Simon, and will include his article, "The Architecture of Complexity," and his comments thereon, coauthored with Mie Augier. In this paper, we comment on "Managing in the Age of Modularity," *Harvard Business Review*, (Sept-Oct 1997).

Our thanks to Barbara Feinberg, who over many years and countless discussions has helped us to develop and refine our ideas. Thanks also go to Masahiko Aoki, Richard Bergin, Wayne Collier, Mark Gaynor, Karim Lakhani, Alan MacCormack, Jan Rivkin, David Reed, John Rusnak, Sonali Shah, Steve Spear, Don Sull, Kevin Sullivan, Jonathan West, Jason Woodard, and members of the Negotiations, Organizations and Markets group at Harvard Business School for sharing key insights. We alone are responsible for errors, oversights and faulty reasoning.

In “Managing in the Age of Modularity,” which was written in June 1997, we proposed that a new technological phenomenon — the *modular design* of complex computer systems — caused the emergence of a large *modular cluster* of firms and markets in the computer industry. We went on to say that “managing” in this “modular environment” was different from managing a large, hierarchical corporation of the type that had emerged in the early 20th Century.[1]

In 1997, there were about 1000 publicly traded companies in the greater computer industry (the figure includes hardware, software and chip makers). Over the next three years (1997-2000), the “high tech” modular cluster grew rapidly both in number of firms and in total market capitalization, only to crash dramatically in 2000 and 2001. In the wake of these events, it is appropriate to reflect on what of actual value resides in modular designs and in the modular cluster as a form of economic organization.

The HBR article was part of a much larger project, which we embarked on 1987, and which continues. To date, we have finished the first of two planned volumes: *Design Rules: Volume 1, The Power of Modularity*. The article introduced several of the concepts found in the book:

- inspired by Herbert Simon (this volume) and Christopher Alexander (1964), it gave a definition of modularity, which others have found useful;[2]
- following David Parnas (1972a, b, 1985), it described how to partition design information into visible design rules and hidden design parameters; and
- it distinguished modularity-in-design from modularity-in-production and modularity-in-use.

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[1] According to Alfred Chandler (1966, 1977), large, “modern” corporations arose as a means of coordinating large-volume, high-flow-through production and distribution systems. Oliver Williamson (1985, Ch. 11) has interpreted the structures of modern corporations (unified and multi-divisional) as responses to potential opportunism (the hazards of market contracting). It is our position that the basic “task structures” and the economic incentives of modular design (and production) systems are different from the task structures and incentives of classic large-volume, high-flow-through production and distribution systems. Therefore the organizational forms that arise to coordinate modular design (and production) may not ressemble the classic structures of the modern corporation. In this respect, we echo Garud and Kumaraswamy, Langlois and Robertson, Sanchez and Mahoney, and Schilling, all in ths volume.

[2] See, for example, Gilmore and Pine (1999).

The article also made several sweeping statements to the effect that modularity was responsible for high rates of product innovation and economy-wide “evolution”:

> Through widespread adoption of modular designs, the computer industry has dramatically increased its rate of innovation. Indeed it is modularity, more than ... any other technology, that is responsible for the heightened pace of change, that managers in [this] industry now face. …
>
> … modularity drives the evolution of much of the economy….

In the article, we did not back up these assertions. In particular, we did not describe the process of modular design evolution, which we were then attempting to explain in our other work. Thus, before proceeding here, we would like to describe briefly the theory on which we based our managerial recommendations. Our theory of modular design evolution can be summarized in two bullets:

- Modularity creates options;
- Modular designs evolve as the options are pursued and exercised.

Each of these points, however, needs some amplification.

1. Modularity creates options.

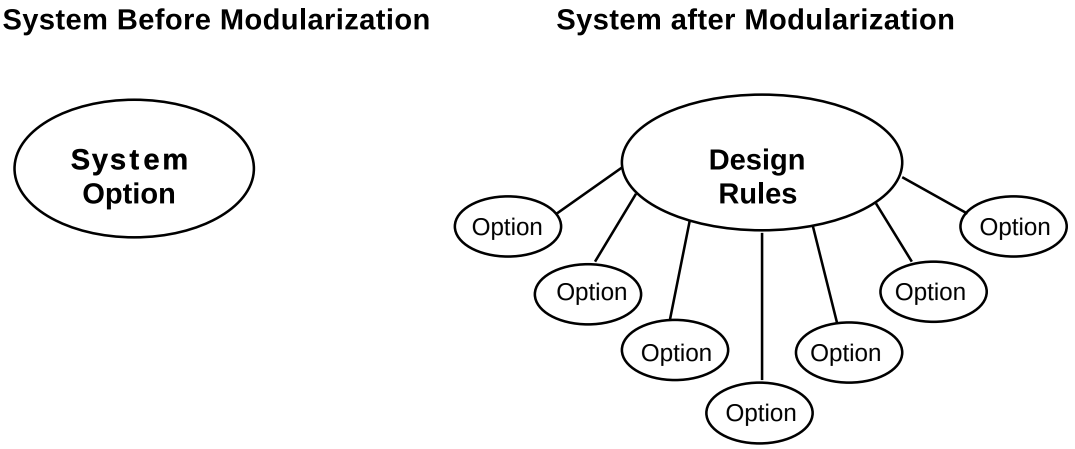
When the design of an artifact is “modularized,” the elements of the design are split up and assigned to modules according to a formal architecture or plan. Some of the modules are “hidden,” meaning that design decisions in those modules do not affect decisions in other modules; some of the modules are “visible,” meaning that they embody “design rules” that hidden module designers must obey if the modules are to work together. (See the inset box “A Guide to Modularity” in the article for further details.) In general, modularizations serve three purposes, any of which may justify expenditures to increase modularity:

- Modularity makes complexity manageable;
- Modularity enables parallel work; and
- Modularity is tolerant of uncertainty.

In this context, “tolerant of uncertainty” means that particular elements of a modular design may be changed *after the fact* and *in unforeseen ways* as long as the design rules are obeyed.

Thus, modular designs offer alternatives that non-modular (“interdependent’) designs do not provide. Specifically, in the hidden modules, designers may replace early, inferior solutions with superior solutions that are subsequently devised. We and several other authors in this volume have said that these alternatives can be modeled as “real options” within the formal theory of finance. Figure 1, taken from *Design Rules*, portrays how the option structure of a system changes as it goes from an interdependent to a modular design structure.[3]

Figure 1
Modularity Creates Options



Source: Baldwin and Clark, 2000, p. 237.

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[3] A “modular design structure” is a particular structure of interdependencies among design or process parameters or, equivalently, tasks. The actual structure of any design or process or any set of tasks can be determined using the “Design Structure Matrix” mapping tools developed by Donald Steward (1981) and Steven Eppinger (1991). For numerous applications of this methodology, see http://web.mit.edu/dsm/publications_name.htm.

The real options in a modular design are valuable. This is not a new or a controversial claim. Building on it, in *Design Rules* we sought to categorize the major options implicit in a modular design, and to explain how each type can be valued in accordance with modern finance theory. The key drivers of the "net option value" of a particular module, we discovered, were (1) the "technical potential" of a module (labeled σ, because it operates like volatility in financial option theory); (2) the cost of mounting independent design experiments; and (3) the "visibility" of the module in question. The option value of a system made up of modules in turn can be approximated by adding up the net option values inherent in each module and subtracting the cost of creating the modular architecture. A positive value in this calculation justifies the investment of resources in a new modular architecture. But how will that value be realized? It will be realized over time via *modular design evolution*.

2. Modular designs evolve as the options are pursued and exercised.

The promise implicit in a modular design is that parts of the system — the modules— can be modified after the fact at low cost. Foresighted actors seeking financial rewards will be motivated to pursue these options, and they will exercise the ones that are "in the money" at some future point in time (the actual date may be uncertain). Exercising an "in the money" option in this case means introducing a new, superior version of a particular module and reaping the economic rewards. The rewards take the form of positive cash flow, from higher product revenue, or lower process cost, or both.

The valuable options in a modular design thus motivate economic actors to pursue innovation, and the exercise of the options constitutes innovation. It follows that a modular design defines a set of evolutionary paths or trajectories in the sense originally defined by Nelson and Winter (1977), Sahal (1983), and Dosi (1988), and developed by many of the contributors to this volume.[4] There will be at least one trajectory per hidden module, and there may be more if the full potential of the actions we call “modular operators” is realized.[5]

As the history of a modular design unfolds, if the promise of the options is realized, we will “see” design evolution. The economically motivated actors in the system will pursue and then exercise design options on the basis of their inherent economic value. Their innovations will cause the individual hidden module designs to change over time in ways that create economic value. Architectures and interfaces will sometimes change, too, but less frequently.

This, we argue, is how innovation works in the microcosm of a modular system. Most changes will not be big sweeping disruptions of the whole, although those are not ruled out. Most changes instead will involve replacing one small modular element with another correspondingly small element that will do the same job in the system, only better. The overall picture is one of ordered, *but not wholly predictable*, progress towards higher economic value over time.

That is our theory in a nutshell. With it in mind, in the HBR article, we urged managers to embrace modularity and its option values, and to design their organizations and strategies with the demands of modular design evolution in mind:

> Being part of a shifting modular cluster of hundreds of companies in a constantly innovating industry is different from being one of a few dominant companies in a stable industry.

3. The dot.com bubble and crash.

But even as the article went to print, events in the economy at large were already beginning to run out of control. In June 1997, the NASDAQ market index was marching

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[4] See David, Langlois and Robertson, Tushman and Murmann and Wade, all in this volume.

[5] Operators are “units of action” in a formal model of a complex adaptive system. The concept is due to John Holland (1992).

upward toward 1500. Its climb continued for almost three years through the first part of 2000: for one brief moment, on March 10, 2000, the index reached the giddy height of 5132. Then it gave back almost all its gains: in mid April 2001, it is hovering around 2000, having closed as low as 1639 on April 4.

The NASDAQ index is both symptomatic and symbolic of the so-called dot.com bubble and crash. Between 1997 and early 2000, thousands of computer software and hardware companies were formed. Several hundred went public. These fledgling companies did not have proven products, much less positive cash flow. Instead they were founded on the basis of product-ideas. According to their virtually universal business plan, if only the idea could be converted from a concept into a real product, the product was guaranteed to play an essential role in the vast new, modular system called the Internet. Revenue, profits, and cash would then flow to the firm that first made the product-idea real.

On this view, virtually all dot.com startups were formed to “pursue the option values inherent in a modular design.” Today, most of them are running out of money, and very few are likely to survive. Large companies are announcing cutbacks and layoffs; smaller companies are going bankrupt or being acquired. For their part, investors have no reason to rejoice: from June 1997 to April 2001, much more value was destroyed than was created in the “modular sector” of the capital markets.

How do we square this bleak reality with the optimistic tone of our article? Can we hold to our theory of modularity as a source of options and and economic value in the aftermath of these events? In fact, the dot.com bubble and crash caused us to reflect critically on both our theory and our optimistic stance. In particular, we asked, in the real world (as opposed to the ideal world, which we modeled), do the benefits of modularity and the modular cluster form of organization justify the costs? If so, when and why?

In the glaring light of current events, we can see some large gaps in our theory. Two, which in hindsight seem especially important, are: (1) how can rational actors calibrate the "technical potential" of a module? and (2) how can rational investors as a group arrive at a sensible aggregate valuation of opportunities, when the opportunities themselves are dispersed in a large modular cluster of firms and markets? In the next sections of this essay, we will explain why these questions are important, and what the answers may imply for the process of modular design evolution in the economy at large. We will then cycle back to the original focus of the article: how does managing in "the modular age" differ from previous ways of managing firms in a market economy?

4. What our theory does and does not predict.

Many aspects of the dot.com phenomenon are wholly consistent with our theory of modular design evolution. Internet protocols, supplemented by the Hypertext Markup Language (HTML), and universal resource locators (URLs) constituted the design rules — the visible information — for a very large and economically potent modular system. Our theory predicts that when the architecture and interfaces of a new modular system become "good enough," hundreds, even thousands, of new design experiments in the hidden modules of the system will become valuable. The architectural transition that multiplies options and option values may arrive quite suddenly, and trigger a wave of investment. Furthermore, if the design rules are not privately owned (and the Internet and World Wide Web protocols are not), valuable options will be accessible to small new firms as well as to established older ones. Thus, in a modular system, it is not surprising to see an investment wave reflected in a wave of entry by small, new firms.[6]

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[6] This thesis was first put forward by Langlois (1992) and Langlois and Robertson (this volume). A formal theory of "the Silicon Valley model" based on information encapsulation and tournament incentives has been constructed by Masahiko Aoki (1999, 2001). Aoki derives what

After the initial "explosion" of options and investment, our theory predicts that candidate designs will compete with one another in a set of "tournaments."[7] In each module category, only one or two solutions will "win" and survive. Tournament competition, we said, would be especially fierce in those hidden modules with the lowest costs of experimentation and the highest technical potential. There, where most of the investment and entry take place, winners will be transient and subject to rapid turnover and substitution.

Hence the great wave of entry and the present "die-off" of Internet firms are fully consistent with our theory of modular design evolution in a large new system with non-proprietary design rules. What was not predicted, and indeed presents a problem for our theory, was the runup and subsequent crash of the NASDAQ Index.

Our formal theory was an equilibrium theory in a stage-game, which we constrained by "rational expectations."[8] Within the framework imposed by rational expectations, *we assumed that the technical potential, σ, of each set of design experiments and the cost of each experiment were known to investors in advance of their investment*. We showed that these two factors together determined the number of profitable experiments that could be undertaken with respect to each specific module in the greater system. In other words, technical potential and experimental cost jointly determined a rational investment rule.

In a group of experiments aimed at a particular hidden module we envisioned the resolution of uncertainty taking place more or less as follows:

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we call a "modular cluster" as an equilibrium institutional form in a set of linked games of R&D and investment.

[7] We adopt this term from Aoki (1999, 2001). Aoki derives tournament competition as an equilibrium incentive mechanism, whereas we see it as an optimal response to underlying real options. In this respect, our theories are complementary (and mutually reinforcing).

[8] In a rational expectations equilbrium of a stage-game, the probabilisitic structure of outcomes is known to all actors before play begins: standard deviations and correlations of the underlying distributions are "common knowledge" to investors in a game theoretic sense. On the constraints imposed by rational expectations in stage-games, see Samuelson (1997) Chapter 1.

1) Initially, every design experiment in a given module category would “carry” value in proportion to its probability of “winning,” (where winning meant emerging as the best design in that category). Thus, if each experiment initially had an equal probability of winning and equal cost to all the rest, then each would have the same economic value at the start of the process.
2) As the process unfolded, one design would emerge as best in each category, and the other experiments would be abandoned. Concomitantly, the sum of economic values in a given category, which was initially dispersed over all design-experiments in the category, would migrate to the winning design and to the firm that owned it.

Thus, we predicted, there would be great turbulence and risk across design-experiments within each category. There would be many starters, many losers, and only a few winners, especially in the low-cost categories with high technical potential. But, we thought much of this risk would disappear in the aggregate. The mathematics of real options and of extreme values pointed in this direction: as is well known, the standard deviation of the *highest* of a set of *independent* trials from a given distribution is much less than the standard deviation of the distribution itself.[9]

Under rational expectations, events in the system might unfold in many different ways, consistent with the underlying distributions, but the investors *ex ante* beliefs about the probabilistic structure would not be disconfirmed by what actually happened. Investors would see after the fact that this design-experiment turned out well, while this

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[9] We did ask ourselves, what if the trials were *not* independent? Then, the mathematics of real options says, each trial or experiment would be worth less. Holding costs fixed, rational investors should then invest in fewer trials, mount fewer experiments, start fewer firms. Thus, under rational expectations, our theory of modular design evolution with independent experiments can explain — rationally — why so many firms were started and then subsequently failed. But it cannot explain why those firms’ aggregate market value rose and fell so dramatically. An alternate theory with correlated experimental outcomes can explain why the aggregate index rose and fell, but it begs the question of why so many *separate* firms were started to pursue essentially similar opportunities. Of course, there is a combination of anticipated independence and correlation that would make what actually happened “just right.” That is an interesting

one turned out badly, but they would have no reason to change their beliefs about the basic probability distributions underlying the experiments. That being the case, investors would have no reason to want to revise their initial investment strategies with respect to module experiments!

Now, we submit, almost anyone who is aware of the dot.com phenomenon has had to change his or her beliefs about the probabilistic structure of the phenomenon. Even those whose expectations about *fundamental value* were essentially correct (i.e., those who identified "the bubble" in 1997 or 1998) have had to revise their beliefs about other people's beliefs, and the effect of others' beliefs on actual market values in the short run and the long run. That means there is almost no one who can honestly claim to have had "perfect rational expectations" about the dot.com phenomenon before the fact.

However, it is possible to move away from the rigid notion of a rational expectations equilibrium and still stay within the framework of a modular system and modular design evolution. If we do so, and assume that costs are generally better understood than probabilities, then two questions immediately arise. First, where do investors get their assessments of technical potential — the implicit σs — which condition their investment strategies? And second, how does knowledge about technical potential come to be "common knowledge" across a group of investors? These are reasonable questions to ask in the context of an evolutionary game, that is, a game played over multiple rounds, in which actors revise their view of the underlying probabilities and the value of strategies as new data come in.

Indeed, it seems unreasonable to believe that knowledge of the probabilistic reward structure of a new modular system would spring fully formed into the minds of investors at the very moment that the system itself came into being. And yet that is what a strict construction of rational expectations would have us assert. We think it is more

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calculation; but to assume that exactly those parameters were actually "expected" and "common knowledge" we think involves a heroic degree of retrofitting of the facts!

reasonable (and interesting) to assume that investors must learn about the probabilistic reward structure of the system through their experiences with investment over time. In an evolutionary sense, investors may even influence the reward structure: it is well known that evolutionary games can develop along different trajectories, each of which provides different rewards for the players. Moreover, the players' interactions and experiences in an evolutionary game may or may not converge over time to an equilibrium set of consistent beliefs and stable strategies.

Thus, the dot.com phenomenon caused us to cut loose from the strict notion of "rational expectations equilibrium" that was inherent in our initial formulation of the theory. We have moved from it toward the more dynamic and provisional notion of equilibria in the setting of evolutionary games. This new framework is leading us to ask new questions: for example, which institutions in a modular system support the formation of consistent beliefs; which beliefs need to be consistent, and which can remain unreconciled; how do different specifications of property rights (e.g., the GNU Public license) affect beliefs about reward structures; and how do anticipated reward structures affect trajectories of innovation at different levels of a modular system?

5. Managing in a modular age

Where does the foregoing discussion take us in our recommendations to managers? We should start by saying that we still think that a modular cluster is a viable and useful form of economic organization in a market economy for industries that "play host" to modular design evolution. Those industries at present include: computers (hardware, software and chip design, though not chip fabrication); financial services; complex assembled goods like automobiles (the design evolution is in their parts, manufacturing processes, and supply chains); and Internet / Web services. In the wake of the dot.com bubble and crash, we fully expect to see a die-off of small firms and financial distress among some large firms in these sectors. But we do not expect to see any of these industries consolidate into a handful of large, vertically-integrated companies. This view of the future, which could be wrong, conditions our recommendations.

For managers in a modular cluster, it is essential (as we said in the article) to "know your product's place" in the design hierarchy of the modular system. Products that are hidden modules, especially small hidden modules with high technical potential, will be subject to very different competitive dynamics than products that embody visible design rules. We would now add: study the modular operators (see Table 1) and the associated option values that are relevant to each of your products. In the operators and their option values reside both the opportunities and the threats to the products' revenue streams.

Table 1
Six Modular Operators[10]

Modular operators form a repertory of actions that can be performed in modular systems. Complex changes in a modular system can be represented as combinations of operators. The value of specific operator-moves can be modeled using real options methods from finance.

Operator	*Definition*
Splitting	Divides an interdependent system into modules
Substituting	Replaces one module with another
Augmenting	Adds a new module to the system
Excluding	Takes a module out of the system
Inverting	Creates new design rules and architectural modules
Porting	Makes a module compatible with two or more systems

We would also say: do not be dogmatic about product and process boundaries. A process can be a module, and, if it is, the process can be a product. In fact, product definitions are endogenous in a modular system. The modular operators can be used to

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[10] This list includes the operators we documented as occurring in modular computer designs, and whose financial valuations we modeled (Baldwin and Clark, 2000). It is by no means an exhaustive list of operators. Other candidate operators are: *replicating* a module; *combining* two or more modules; and *extending* a module. The identity and valuation of operators is an open line of research in the economics of modular designs.

create new modules that can become new products, hence serve as the basis of new firms. As a result, products and firms will be ever-changing in the presence of modular design evolution. In addition, the greatest “turbulence,” that is, the most rapid turnover of designs, will predictably arise in the small hidden modules with high technical potential: this is true whether the modules are specified as tangible objects or intangible processes. *Caveat factor*: the makers of modules should beware, because their products can be replaced.

In the article we emphasized that the internal organization of a firm — of any size — needed to reflect the modular structure of its products and processes, and to allow for decentralized, independent exercise of modular options. Unambiguous, binding design rules and simple, objective criteria of success and failure were desirable features for organizations competing for value in an evolving modular system. We would echo those recommendations today. Recent empirical work by Richard Bergin (2001) on the relative performance of Internet startups with a range of internal structures and organizational philosophies has increased our confidence in this claim. His results indicate that carefully designed “rules hierarchies” that match the modular structure of a firm’s products and processes increase its likelihood of success in the tournament-type competitions, which are characteristic of evolving modular designs. In effect, the “guidance rules” and internal modularity of products and processes support efficient, repeated plays for valuable market positions. These plays can occur in rapid sequence or in parallel: a modular organizational structure supports them by holding down organizational complexity; by enabling parallel work; and by permitting adaptive responses to new market developments.

We would also say to managers that a cluster of firms and markets is by no means the only way to organize a modular system, nor is it necessarily the most efficient way to instantiate modular design evolution. To our knowledge, at least two other, quite different, forms of organization have also succeeded in first starting up, and then “hosting” modular design evolution over relatively long periods of time. These are the Toyota Motor Corporation and the Open Source Software development community: their modular systems are, respectively, the Toyota Production System (TPS),[11] and a set of stable and evolving open-source code bases including Apache and Linux. Indeed, we think that Toyota and the Open Source developers have managed to “drive” the principles of modularity “deeper” into their design hierarchies than any cluster of firms and markets — given their implicit coordination problems — would be able to do.

Thus, taking full account of the events of the last four years, we would still end on an optimistic, albeit cautionary, note. We believe that “the modular age” can be and should be an age of opportunity. Modularity is a powerful design principle, and the modular operators as a group are demonstrably generators of opportunities and option value. In addition, as we said, the modular cluster form of organization is both viable and useful in a market economy. It is here to stay, although (we now see) clusters need institutional mechanisms for coordinating beliefs, and these institutions themselves are still evolving. Finally, even in a cluster, there will be opportunities to create modular systems and reap the benefits of modular design evolution within individual firms. For managers and for the rest of us, the greater peril lies in ignoring the potential of modularity.

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[11] For an analysis of the design rules and modular structure of TPS, see Spear (1999), especially Chapter 1 and pp. 160-165.

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