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The Option Value of Modularity in Design

An Example from
Design Rules, Volume 1: The Power of Modularity

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Abstract

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.

Modular designs offer alternatives that non-modular ("interdependent') designs do not provide. Specifically, in the hidden modules, designers may replace early, inferior solutions with later, superior solutions. Such alternatives can be modeled as "real options." In *Design Rules, Volume 1: The Power of Modularity* (MIT Press, 2000) 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. This paper provides an example of the valuation of the modular options "splitting" and "substitution."

We show that the key drivers of the "net option value" of a particular module are (1) its "technical potential" (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 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 investment in a new modular architecture.

1 An Overview of the Research

We are seeking to develop a technological theory of *modularity* and *design evolution* that can inform economic theories of industry evolution. Using the computer industry as a defining example, our book, *Design Rules*, explains:[1]

- what modularity is and how it can be attained;
- how modularity makes it possible for designs to evolve in a localized fashion (modular design evolution);
- how economic incentives operating at many points in a modular design eventually may lead to the emergence of a "modular cluster" of autonomous firms;
- how modular designs create economic conflicts whose resolution may require new institutions regulating finance, employment and intellectual property within the cluster.

The best way to motivate the study of modularity is to show the effect it can have on the structure of an industry. We collected data on the market values of substantially all the public corporations in the computer industry from 1950 to 1996, broken out into sixteen subsectors (see Figure 1). The data tell a story of industry evolution that runs counter to conventional wisdom. The dominant theories of industry evolution describe a process of pre-emptive investment by large, well-capitalized firms, leading to stable market structures and high levels of concentration over long periods of time.[2] Figure 1 shows that there was indeed a period in which the computer industry was highly concentrated, with IBM playing the role of dominant firm. (IBM's market value is the blue "mountain range" that forms the backdrop of the chart.) But in the 1980s, the computer industry "got away" from IBM. In 1969, 71% of the market value of the computer industry was tied up in IBM stock; by 1996, no firm accounted for more than 15% of the total value of the industry.

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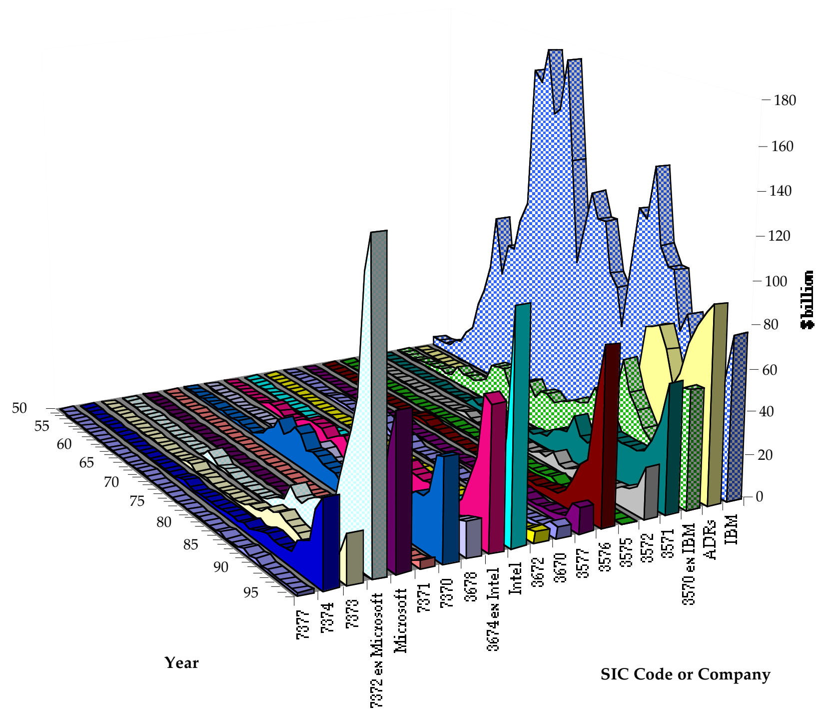
[1] The arguments and all figures in this paper are taken from C.Y. Baldwin and K.B. Clark, *Design Rules, Volume 1: The Power of Modularity*, © MIT Press, 2000, reprinted by permission. Volume 2 is in progress.

[2] The original theory of pre-emptive investment leading to industry concentration, with supporting historical evidence, was put forward by Alfred Chandler (1962, 1977). A complementary theory of concentration following the emergence of a "dominant design" was put forward by William Abernathy and James Utterback (1978). Modern formulations of these theories and some large-scale empirical tests have been developed by John Sutton(1992) and Steven Klepper (1996). 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.

Figure 1
The Market Value of the Computer Industry
By sector, 1950-1996 in constant 1996 US dollars



Source: Baldwin and Clark, 2000, Plate 1-1.

By 1996, the computer industry consisted of a large *modular cluster* of over 1000 firms, no one of which was very large relative to the whole. The total market value of the industry, which increased dramatically through the 1980s and 1990s, was dispersed across the sixteen sub-industries. Finally, the connections among products in the subindustries were (and are) quite complicated. Most computer firms did not design and make whole computer systems. Instead they designed or made *modules* that were parts of larger systems.

In *Design Rules*, *Volume 1: The Power of Modularity*, we argue that a fundamental *modularity* in computer designs caused the industry to evolve from its initial concentrated structure to a highly dispersed structure. Modularity allows design tasks to be divided among groups that can work independently, and do not have to be parts of the same firm. Compatibility among modules is ensured by "design rules", which govern the architecture and interfaces of the system. The design rules must be adhered to by all, and hence can be a source of economic power to the firms that control them.

Our theory of modular design and design evolution can be summarized as follows:

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

We explain and amplify these points below.

2 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.

In general, modularizations serve three purposes, any of which may justify an investment in 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 later, superior solutions. Such alternatives can be modeled as "real options." Figure 2 portrays how the option structure of a system changes as it goes from an interdependent to a modular design structure.[3]

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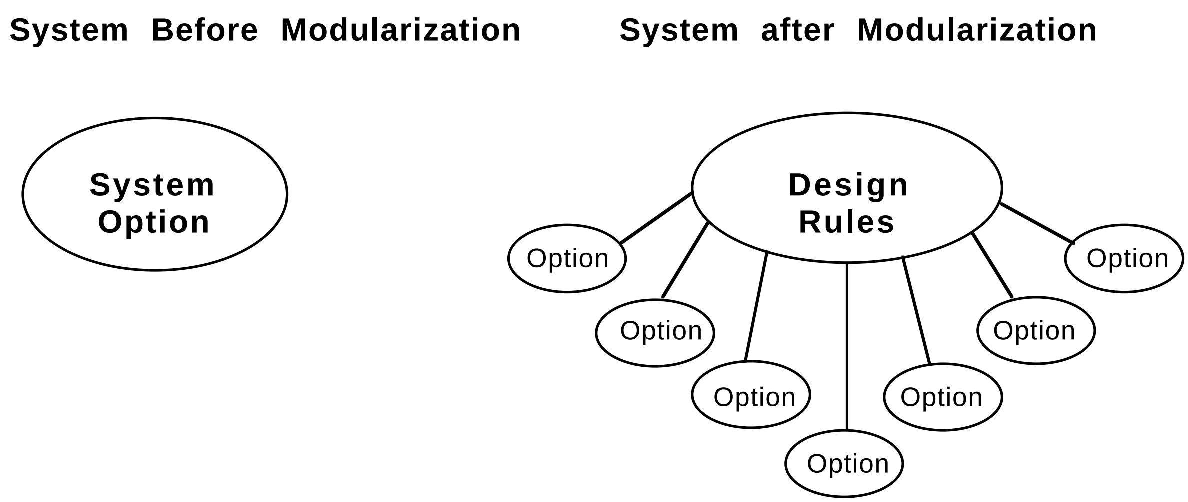
[3] A "modular design structure" is a particular structure of interdependencies among design or process parameters or, equivalently, tasks. The actual structure of any design or process or any set of tasks can be determined using the "Design Structure Matrix" mapping tools developed by Donald Steward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

Figure 2
Modularity Creates Options



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

The real options in a modular design are valuable. 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 are (1) the "technical potential" of the 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 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 investment in a new modular architecture.

2.1 An Example: The Value of Splitting

As an example, let V_1 denote the value of a one-module design with N tasks. Assume that the final outcome of the design process, denoted X, is a random variable that is normally distributed with mean zero and variance $\sigma^2 N$. Consistent with this being a one-module design, once the designers finish their task, they can only take the new design or leave it. The value of the new design *if it is superior to the old one* (whose value is normalized to zero), is:

$$V_1 = S_0 + E(X_N^+) \quad ; \qquad (1)$$

where E( ) indicates "expected value" and X has a normal distribution with mean zero and variance $\sigma^2 N$. The "+" superscript on X means that the expectation applies only to outcomes above zero.[4]

Now let us suppose a design process is partitioned into j independent modules, while the number of tasks, N, remains the same. The expected value of the modular design, denoted V_j , is then:

$$V_j = S_0 + E(X_1^+) + E(X_2^+) + \ldots + E(X_j^+) \quad ; \qquad (2)$$

where X_i is the contribution to overall system value of the ith module. Equation (2) indicates that each module's value can be compared to the benchmark established for that module. If the new module design has value greater than zero, meaning that its performance in the eyes of consumers is superior to the existing one's, the new design will be incorporated into the system. Otherwise the existing design will continue to be utilized.

As long as the distribution of the sum of module values remains the same as before the split, the modular approach is bound to yield a higher total value than the unmodularized approach. For one thing, the modular designers could tie their own hands and commit to take all or none of the new designs. If they did so, they could expect their design to perform as well as a corresponding one-module design. However, the modular designers can also consider module-level improvements. These options only add to the value of the whole. Mathematically, the

[4]More formally,

$$E(X^+) = \int_0^\infty X\, f(X)\, dX \quad ;$$

where f(X) is the density of a normal distribution. We use the simpler notation throughout the text. In the interest of simplicity and clarity, we also suppress adjustments for time and risk.

option values are reflected in the fact that each expectation in equation (2) ranges over the positive half of a probability distribution; realizations that are negative (i.e., fall short of the existing design) will be culled out.

Thus, holding the distribution of aggregate value fixed, higher degrees of modularity increase the value of a complex design. This result is a special case of a well-known theorem, first stated by Robert Merton.[5] For general probability distributions, assuming aggregate value is conserved, Merton showed that a "portfolio of options" is more valuable than an "option on a portfolio."

More generally, let X_α be the performance of a module of size αN. By assumption, X_α is a random variable, normally distributed with mean zero and variance $\sigma^2(\alpha N)$. We define z_α as follows:

$$z_\alpha = \frac{X_\alpha}{\sigma\,(\alpha N)^{1/2}} ;$$

z_α is normally distributed with mean zero and variance one.

Substituting standard normal variates in equation (2), dropping S_0, and collecting terms, we have:

$$V_\alpha = \sigma N^{1/2} \left(\alpha_1^{1/2} + \alpha_2^{1/2} + \ldots + \alpha_j^{1/2} \right) E(z^+) ; \qquad (3)$$

where $E(z^+)$ is the expectation of the right tail of a standard normal distribution and equals .3989.

In this fashion, we can compare the value of a modular design to the value of a corresponding unmodularized effort. We summarize the relationship in the following proposition:

Proposition 1. Under the assumptions of our model, let a design problem of complexity N be partitioned into j independent modules of complexity ($\alpha_1 N$, $\alpha_2 N$, ... , $\alpha_j N$). The modular design has value:

$$V_\alpha = \left(\alpha_1^{1/2} + \alpha_2^{1/2} + \ldots + \alpha_j^{1/2} \right) V_1 ; \qquad (4)$$

relative to V the corresponding unmodularized design effort.

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[5] Merton, 1973.

Proof.

By definition, a one-module design has both j and α_j equal to one. Thus $V_1 = \sigma \ N^{1/2} E(z^+)$. Collecting terms and substituting in equation (3) yields the result.

From the fact that $< \alpha_1, \alpha_2, \dots, \alpha_j >$ are fractions that sum to one, it follows that the sum of their square roots is greater than one. Thus, as expected, if we ignore any change in system value and the costs of achieving modularity, a modular design is always more valuable than the corresponding non-modular design. Moreover, additional modularization increases value: if a module of size α is split into sub-modules of size β and γ, such that $\beta + \gamma = \alpha$, then the subdivided module's contribution to overall value will rise because $\beta^{1/2} + \gamma^{1/2} > \alpha^{1/2}$.

2.2 The Value of Parallel Experiments (Substitution)

In the previous section, we assumed that designers would create only *one* new design per module. However, they could as well decide to run several parallel experiments on each module and select the best of these outcomes. How much better is the first-best from the second- or third-best experimental design? The answer to this question is the value of the modular operator we call "substitution." Intuitively, a modular design decouples experiments, and allows designers to substitute a superior design for an inferior design of any module.

To quantify the value of substitution, let us suppose that for a module comprising n tasks, the designers initiate k parallel, independent design efforts. They then have the option to select the best of k outcomes for the final design.[6] Let Q(X; k) denote the "value of the best of k designs" as long as it is better than zero, for a random payoff function X.[7] The value of a design process with j modules and k_i experiments in the ith module is then:

$$V(X_1 \dots X_j ; k_1 \dots k_j) = S_0 + Q(X_1; k_1) + Q(X_2; k_2) + \dots + Q(X_j; k_j) \qquad (5)$$

Like equation (2), equation (5) is a "portfolio of options" result that applies to any set of probability distributions, as long as the total system value is conserved, and module values are

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[6] Stulz, 1982, provides a general analysis of parallel options in his valuation of the option to select the maximum of two risky assets.

[7] This distribution of the best of k designs is well known in statistics: it is the distribution of the "maximum order statistic of a sample of size k." Lindgren, 1968.

additive. But, again, it is too general to be of much use. We can gain additional insight by focusing on normal distibutions and symmetric modules.

In general, the appropriate number of experiments to run on a module depends on that module's technical potential, complexity, and visibility to other modules. If, however, we assume that modules are symmetric, then it will be optimal to run the same number of experiments on each module. The 2j arguments in equation (5) then collapse to two, and the value of the design process as a whole, denoted V(j,k), is:

$$V(j,k) = S_0 + \sigma (Nj)^{1/2} Q(k) \qquad (6)$$

2.3 The Costs of Modularity

Modularity creates value but it is not free. There are, first of all, the costs of making an interdependent system modular: the cost of creating so-called "hidden modules" and disseminating design rules. The process of of modularizing a complex system is generally a lengthy, pain-staking process for e*very important design dependency must be understood and addressed via a design rule.*

Obviously the density of the dependencies matters here: some systems are naturally more "loosely-coupled" than others. Circuits, the physical system on which computers are based, are one-dimensional; whereas mechanical solids are three-dimensional. Clearly it is harder to split up complex, curved, 3-dimensional designs, and to create flexible interfaces for them: there are more dependencies to manage, and the tolerances are much tighter. Thus modularizing an automobile's design is a tougher problem than modularizing a circuit design: the cost of creating a modular architecture and related interfaces for an automobile will be higher than for a VLSI circuit.[8]

It is also costly to run the experiments needed to realize the potential value of a modular system. Finally, it is costly to design the tests that are needed to determine whether specific modules are compatible with a given system, and which modules perform best. The costs of

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[8] This has led some scholars, like Daniel Whitney at MIT, to predict that autos and airplanes will achieve only limited modularity in practice. If that is so, the option values of such systems will be limited in relation to systems that *can* be modularized. See Whitney, 1996; Sharman, 2002; Sharman, Yassine and Carlile, 2002.

architecture, experiments, and tests are all inherent in the modular design process itself. The interaction of option value and these costs causes each module in a large system to have a unique value profile.

Additionally, if the module experiments are distributed over a cluster of independent firms, there will be transaction costs: what Ronald Coase labelled "the costs of using the market."[9] As designs and/or physical artifacts are transferred from enterprises working on modules to enterprises working on systems integration and testing, there will be costs of search and price determination. Hence, the division of modular design efforts across a decentralized cluster of firms will multiply transaction costs in the same proportion that it multiplies modules and experiments.

Last but not least, agency costs and costs of opportunistic behavior are implicit in the modular system and its institutional surroundings. There may be opportunities for the architects of the modular system and the systems integration and testing groups to "hold up" other parts of this system by threatening to withdraw their services or their intellectual property. In other words, there are potential "points of control" in the modular system. This in turn means that the distribution of value across agents and the dynamic evolution of the system itself will depend on the allocation of key property rights: for example, who owns the architecture? Who owns the interfaces? Who has rights of access to design information? Who has rights of exclusion?

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

Modular designs create value in the form of valuable real options. But how will that value be realized? In *Design Rules*, we argue that the value of a modular system will be realized over time via *modular design evolution* (MDE).

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 thus 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 may take the form of 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 others.[10] 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.[11]

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.

[9] Coase, 1937.

[10] See, for example, David, 1987; Langlois, 1992; Langlois and Robertson, 1992; Tushman and Murmann, 1998.

[11] Operators are "units of action" in a formal model of a complex adaptive system. The concept is due to John Holland, 1992.

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