For us who manifest our will in the material of our environment, there is a tendency to define beauty as the resonant chorus of every detail in our work. Against this asymptotic ideal, the fleeting notion of striving for less than perfection elicits a giddy vertigo from which we recoil in disgust. Ours is surely the high ground! Yet we are perched in a precarious position; like the characters in Sherwood Anderson’s Book of the Grotesques, we must forever bear the weight of our religion or become grotesques ourselves.

It is for you that we,
the fallen among us, erect this
new definition of beauty at the
trailhead of your path.

Low Risk	↔	High Risk
Lightly Constrained	↔	Heavily Constrained
Large Material Gamut	↔	Small Material Gamut
Malleable Form	↔	Rigidly Defined Form
Low Tolerances	↔	High Tolerances
Fit “to Taste”	↔	Predefined Fit
High Tool Accesibility	↔	Low Tool Accesibility
Rapid Geometric Feedback	↔	Delayed Geometric Feedback
Rapid Functional Feedback	↔	Delayed Functional Feedback
Evolution	↔	Intelligent Design
Poor Intuitive Model	↔	Good Intuitive Model
Poor Mathematical Model	↔	Good Mathematical Model
Low Manual Skill	↔	High Manual Skill
Low Design Skill	↔	High Design Skill
Non-Linear Return on Time Investment	↔	Linear Return on Time Investment
Shallow Learning Curve	↔	Steep Learning Curve
Loosely Coupled Functionality	↔	Highly Coupled Functionality

Gestural Design

A Treatise

Ilan E. Moyer

Gestural Design:
A Treatise

First Printing, July 2013.

To my friend, Greg Schroll.

Typeset with the font Menlo by Jim Lyles
Printed at AS220 in Providence, RI.

It takes a lifetime to become young.
—Pablo Picasso

Preliminaries

It has been observed that fields which become coupled to computer science begin to grow at a similarly exponential rate[1]. It has also been observed that every work of art is a self-portrait[2].

In the way that we conceive and birth objects, a process that once was craft now begins to ever more resemble the computational machines which we use to create. The chasm between design and fabrication is widening; we have become programmers, and our computers (and the tools that they control) have become the compilers of real objects that run as programs on the “hardware” of our environment.

At the limit of this rapidly accelerating future, one can easily imagine a day when we conceive of an object and it is produced automatically and immediately before our eyes. The fact that we no longer possess the skills to directly manipulate the substance around us will on this day finally be irrelevant. But somehow this outlook feels empty; distant in our wake will lie abandoned the joy which used to reside in our hands.

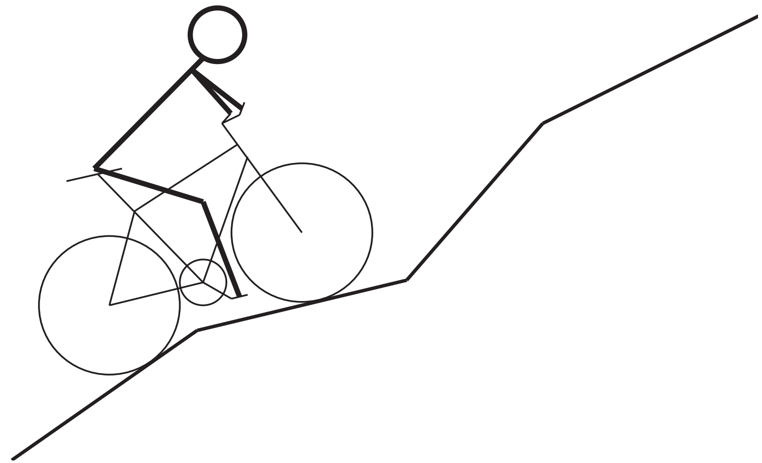
So let us imagine a parallel future in which everything is to our hands *as if* it is made of clay. In this alternate existence, products aren’t born perfect (or less perfect, depending on what you pay) – its denizens do not believe in the existence of a single absolute standard of perfection delivered from on-high. In fact, the notion of static perfection is, for them, something of a joke from a time long since dismissed.

The measure of beauty in the clay-world is one of **matched impedance:** how well do the objects which surround us match their purpose, and how easily can we modify them to better suit our needs?

The pages of this book hope to serve as a bridge to the shores of the clay-world that might yet be.

1) Ray Kurzweil in his presentation at the MIT Enterprise Forum in October, 2009. 2)I first heard this from Myron Barnstone at the Barnstone Studios in Coplay, MA.

Universal Principle of Matched Impedance



If you have ever ridden a bicycle – especially a single speed bike – the concept of matched impedance is familiar to your legs if not also to your brain. In order to climb a particularly onerous hill you might pedal extremely slowly, wondering at times if you are capable of exerting the force necessary to keep moving. Suddenly the bicycle becomes the focus of your attention: you notice every degree of rotation that you manage to coerce out of the crank arm.

On your way back down, the situation reverses. With your legs spinning fast-as-they-can, the bicycle settles at a top speed seemingly irrespective of your contributions. Now it is your legs that are opaque. If only they were a bit lighter and able to whip around even faster, you could apply some force to the pedals and accelerate.

The joy of cycling is at neither of these extremes. There exists a feeling, which we occasionally achieve, when the bicycle and our legs meld into one and we feel the road. Power is effortlessly transmitted from our muscles to the wheels and converted into motion. Not only do we feel acceleration; we feel *control*. The results of our intent are immediately transmitted back to us as action. In this moment we experience the magic of matched impedance.

The term *matched impedance* has its origins in engineering. It can be shown that a motor will accelerate a load (such as vehicle) the fastest when the effective impedance of both are equal. In the field of electronics, impedance mismatches cause signals to bounce back to the sender rather than transmit in their entirety. This effect can be seen when playing pool – a direct hit brings the cue ball to an immediate stop while the struck ball speeds off with hardly any energy lost in the exchange. This would not be the case if the cue ball was replaced with a whiffle ball, or a bowling ball. Matched impedance explains why a metal surface feels cooler (or hotter) to the touch than a plastic one, and why propeller blades are shaped differently for airplanes than they are for boats.

Nowhere is this practically universal principle more important than in our dear field of creation. In order to better understand the value of matched impedance to us as shapers of our world, let us consider the relationship between our brain and our environment. In isolation, our brain is utterly impotent to affect change outside of itself: our body must serve as the connection between our consciousness and the environment in which we exist.

Eyes convert light into neural signals, and hands convert signals into action.

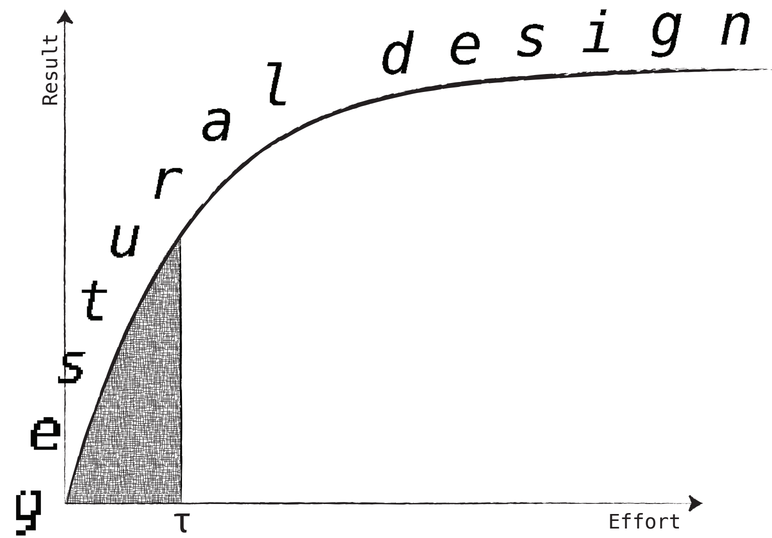
It is frequently the case that two objects with mis-matched impedances are forced to work together. A bike rider and the hills of San Francisco for example. Seeing as neither will readily change to suit the other, we employ what engineers call an *impedance matching device*. In the case of the cyclist, this comes in the form of gears. For electrical signals the analog is called a transformer. And Nature has provided our brains with an extremely adaptable impedance matching device – our body.

Our hands are fast, nimble, and soft. As the potter and the pianist will attest, our hands become transparent[3] when they work at tasks well-matched to their abilities. When this is the case, it feels as if our brains are directly coupled to our environment. But as soon as we attempt with our bare hands to execute a simple but mismatched intent such as driving a nail, the illusion of transparency is shattered.

For many of our daily tasks, and particularly when we create, we require something extra to adapt ourselves to our work. Tools pick up where our hands, and brain, leave off. Some tools are like the low gear on a bike... one push and you're flying. A calculator accepts a simple input and spares your mind the tedious computations necessary to yield an answer. Other tools, like a hammer, act more like high gear. A slow swing of the hammer over a long distance results in incredible force over a short distance. From an engineering perspective, a hammer is quite similar to a gear box. Even the design of a hammer is indicative of its impedance-matching role: a relatively soft wood or rubber handle couples the tool to our hands, while a hard and tough steel head is well suited to interact with a nail. Tools are by their nature impedance matching devices.

3) The notion that good tools are transparent comes from Malcolm McCullough's 'Abstracting Craft,' and fits well into the framework of tools as impedance matching devices.

Design in the First Time Constant



Nothing can accelerate forever. Even the fastest race cars gain speed quickly at first, and then eventually settle at a maximum velocity. Air drag — an opposing force proportional to velocity — conspires to increasingly sap power from the car's engine as it gains speed. At a certain point the engine is completely occupied with overcoming drag and a terminal velocity is reached. Many physical phenomenon exhibit analogous asymptotic behavior. A glass of cold water left outside on a hot summer day warms rapidly at first, but then begins to gradually approach (but never reach) the temperature of its environment. This tapering path from one state to another is known as bounded exponential growth. The time it takes for the water to warm by 63% of the temperature difference between itself and its environment is known as the **time constant** of the growth.

Design is asymptotic. Huge visible progress gets made in the initial phase where the design space is explored and stakes are planted in the ground. Rough prototypes made from easily formable materials might embody 80% of the functionality of the finished product in only a small portion of the total project duration[4]. Artists have a similar practice called gesture drawing which they use to rapidly express and test ideas. A quick thumb sketch can capture most of the relevant details of a subject or idea in a fraction of the time required for a full rendering. As you traverse the narrowing funnel of the design process, the rate of progress begins to slow. Details must be resolved, both against themselves and as they relate to each other. This process which began with concept-driven acceleration soon feels the viscous drag of implementation. Perfection lies always ahead, forever nearing but never here. The challenge faced by designers is two-fold: figuring out how to accelerate a design the fastest, and deciding when to stop. The bounded exponential growth curve is a lens through which we can explore these fundamental problems in the design of objects.

In the graphic beginning this section, the letters of ‘gestural design’ are each rendered with proportionally more resolution. At the very beginning of the refinement process the question is one of economy: how few pixels are necessary to convey the letter ‘g’? Everyone would agree that to use any fewer would be a waste of effort (of

design, information, ink, paper, etc.), as you might as well leave the space blank. As you traverse up the curve, the question begins to become one of saturation: when does the resolution of the character exceed that of the printing process? The last couple letters look practically identical for this reason. Many would agree that additional effort beyond this saturation point is wasted as well. **We maintain that it is exactly at these two points – maximum economy and saturation – where an object possesses the property of integrity**. These are the only two states in which the object *makes sense*. At all other points material and/or effort is wasted. Integrity is the answer to the question of when it is time to stop.

It seems natural to see integrity in an object which has been brought to the point of saturation, where perfection has been achieved to within our limits of perception. These objects are (and must be) highly designed: details are tightly integrated, all excess has been removed by combining common-mode functionality, and great care has been taken to produce a pristine finish. Such a specimen is at a perfect state of matched impedance with its ideal. The problem with this type of integrity is two-fold. First, it requires an enormous amount of effort to achieve. Along the onerous climb to its realization lie the corpses of almost every mass-consumer product manufactured today. However, the more important problem with perfection as a goal is the implied notion that the standard of perfection is absolute and invariant. Objects designed this way make ideal museum pieces, freezing in the web of their highly resolved details the reflection of a truth that once was. But in our world of shifting needs and perception, these children of isolation inevitably become grotesque. Because their design is so carefully conceived, so monolithic, it is impossible to ex post facto modify their manifestation without desecrating their integrity. The concept of integrity through perfection is dangerous to design for precisely this reason.

We see integrity in objects that have just emerged from the clay. They are still wet; still soft in our hands. Raw and conceptually naked, such items are at once sensitive to our whim and us to their driving idea. These are not the furniture we are afraid to use lest we spill our drink, or the computer from which we still haven't removed the protective plastic sheet years after purchase. Nor the washing machine that is cheaper to replace than it is to repair the plastic coupling which always fails first.

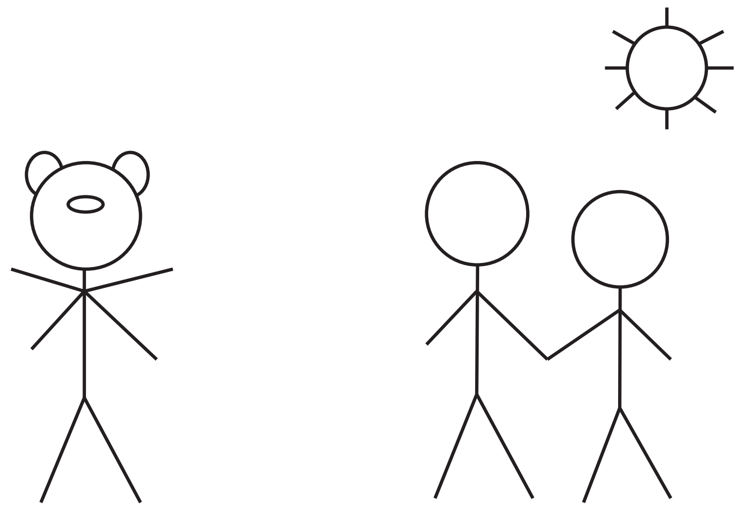
We see beauty in the first time constant. Objects born at this stage in their development – at a point of maximum economy – exist in a state of matched impedance both with their creator and with their audience. There is a symmetry between the process by which an object is designed and the place it takes in our lives. 'Perfect' objects are inorganic by their premise, their soul forever locked in a body too complex and rigid to truly commune with ours. They are condemned to cohabit our world, and to be eventually killed or enshrined. The latter fate being a landfill for the sentimental. 'Raw' objects (whose integrity is derived from the clarity of their central idea) are made of the same stuff as us, have the same impedance as us, and become beloved.

The problem with this premise, that we should stop before an object becomes Designed, is apparent. What would a world be like where everything is unfinished? (A MORE TRUTHFUL WORLD, interjects our wise-ass doppelganger). This is both an aesthetic and a practical question. Beauty is commonly associated with perfection – a troublesome state of affairs considering the temporal whimsies of style and planned obsolescence[5]. (It is interesting that the only domain which seems immune to our shifting notion of beauty/perfection is organic Nature). We advocate a new definition, where something is considered beautiful based on our ability to bend it to our own aesthetic. The result would be artifacts which truly have character, and which demand of us their continued evolution.

The practical concerns require more than just a cultural shift. New tools must facilitate a continuous impedance match between us and our work. These may be physical objects themselves, or techniques and processes by which we use other tools. The key to the clay world is that it feels to our hands like clay. It is our tools that will provide this sensation by adapting both our actions and our senses. When this is achieved, our souls will become coupled to those of the objects we design and creative energy will flow freely. The boundaries between design, fabrication, and consumption will blur.

4) The Pareto principle, proposed by Joseph Juran. Also known as the 80/20 rule. 5) See Vance Packard's 'The Waste Makers' for a definition of planned obsolescence via manipulation of desire rather than mechanical failure.

Evolution and Intelligent Design



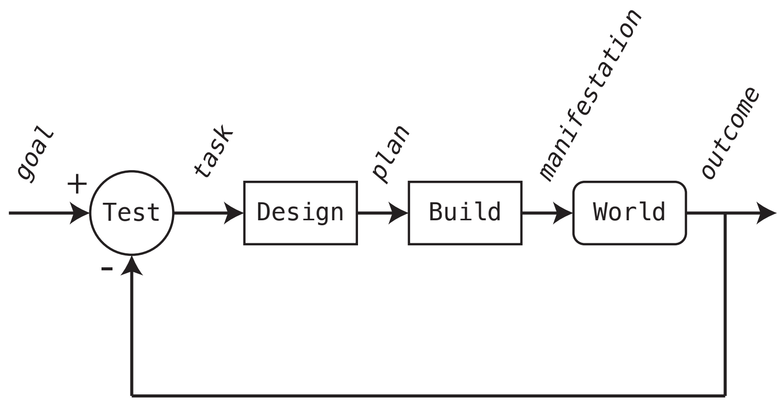
Two theories explain how life on this planet was fashioned. The biblical theory holds that an all-mighty Creator intentionally premeditated, or *designed*, all that is natural around us. *And it was so*. Intelligent design represents design in its purest ivory tower form, absolutely divorced from manifestation. This requires an omniscient creator capable of predicting exactly how something will function a-priori and for whom the representation of a design is exactly equivalent to its manifestation. When this latter assertion is true, fabrication becomes an irrelevancy reduced to whether something is or isn't. Like whether you, wielding a marker before a piece of paper, decide to leave a dot.

The evolutionary theory proposed by Charles Darwin in the 19th century sees life as the result of a highly parallel process of trial and error, each successful experiment seeding the next and converging on the myriad of species which inhabit this earth. Evolution is design in the real world: the utter union of design with the act of creation. So complete is this marriage that one might question whether it is a misuse to invoke the word *design*. After all, can a process which in its abstract form lacks any intelligent guidance, be considered design?

If intelligent design is pure thinking, evolution is pure doing. A creation process based entirely on the former must get everything right on the first try. This requires infinite pre-planning – and infinite time – to ensure that a design is perfect before making it real. Conversely, a process based entirely on evolution would be constantly making things real. Progress would be steady but incredibly slow because without the guiding hand of forethought, the process is one of random trial and error. To us humans, intelligent design is like trying to bench-press a weight far too heavy to lift. Evolution is bench-pressing without a weight. Both extremes represent severe impedance mismatches between us and our work, where no power transfer can occur.

The theories of evolution and intelligent design represent diametrically opposed extremes which bound the spectrum of design processes used by humans to bring new objects into existence. It is by strategically mixing both approaches that we craft process-tools which best accelerate our own attempts at creation.

Closed Loop Design



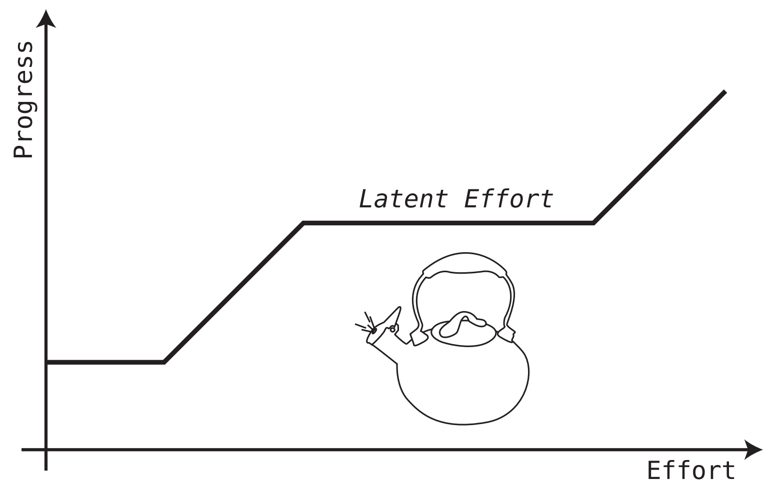
One of the great engineering answers to the problem of intelligent design – a perfect solution requiring an infinite amount of pre-planning to achieve – is the feedback loop. Rather than understanding a problem in its entirety up-front, feedback control tries a solution, measures the error between the desired and actual results, and then iteratively compensates over the course of subsequent attempts. In 1788 James Watt (for whom the standard unit of power is named) applied feedback control to the steam engine through the use of the flyball governor and thus enabled the industrial revolution. Until this moment in history, steam was impractical as a safe source of power because the pressures inside the engine were difficult to predict and thus control "open-loop."

Control systems are typically represented as a block diagram with three components: the controller, the plant, and a summing junction. The controller is the intelligence of the feedback loop, responsible for deciding what action to take in the face of error. The plant is the system being controlled – a physical interaction between the controller and the environment. The summing junction compares the reaction of the plant with a desired outcome and reports discrepancies. Together, these three elements represent one cycle around the control loop.

A well-designed control loop is tuned to the system it is trying to control: it doesn't attempt to achieve a perfect solution in a single iteration, but neither does it take overly-timid and uninformed steps. It is the strategic (and dynamic) amalgamation of intelligent design with evolution that will yield a control loop most capable of accelerating our design efforts. In lieu of the controller we substitute "design," the plant becomes "build," and the summing junction "test." This cycle of design -> build -> test[6] is the process-tool which we apply iteratively to match impedances between our goals and the problems that we face as we ascend the asymptotic curve of creation. Like racing a bike, the best results rely on knowing when and how to switch gears. And towards this end, there is another physical phenomenon from which we can learn…

6) Related to the MIT Course 2.009 motto 'Ideate, Model, Test!' which is taught by Prof. David Wallace.

Latent Effort



Imagine heating a pot of water on the stove. As energy is pumped into the water by the heating element, the water's temperature rises. This process is linear – the temperature of the water increases steadily as energy is transferred to it by the stove. Suddenly, the water temperature flat-lines at 100°C. Continued application of heat has no measurable effect. To say that nothing is happening, though, would be a mistake. It is during this period of constant temperature that the water is boiling and changing into steam. Scientists call this transition a *phase change*, and the energy required **latent heat.** If you were able to contain the steam in a sealed pot and continue to heat it on the stove, its temperature would again begin to rise linearly. Energy whose effect can be directly measured as a change of temperature is known as **sensible heat.**

When we alloy the pure processes of evolution and intelligent design, we yield the atomic unit of practical design processes: the cycle of design -> build -> test. The first two stages represent the **latent effort** of the cycle, where work is invested without a visible return. Only during the testing phase does our effort become sensible and the progress embodied in the cycle becomes measurable. A typical design process might include many iterations of this fundamental cycle, each of which is intended to propel us further down the asymptotic curve of design. If we were to zoom in on the bounded exponential curve, we would likely see that it isn't smooth but rather stepped.

The various fields of engineering have distinctly different durations and ambitions for each iterative cycle. Software and electronic development practices emphasize modularity through the use of libraries and integrated circuits, respectively, which dramatically reduces design times by permitting the reuse of modules. This allows developers to focus on novel contributions rather than reinventing (or at least re-implementing) the wheel. For these disciplines, the cost of modularity is often negligible compared to the benefits. Rarely will a software engineer need the performance boost afforded by writing directly in machine code, nor will most electrical engineers design their own silicon chips to save space on a circuit board. Mechanical engineering benefits from some degree of modularity with off-the-shelf components such as ball bearings and fasteners, but its price is much greater than in other domains. Extraneous waste, excessive bulkiness, needless

cost – in a word, aesthetics[7] – drive the mechanical engineer to redesign elements which have been designed countless times before: hinges, flexures, latches, threads, to name only a few, are re-implemented so that they can be integral to a design rather than agglomerated.

Design time is one contribution to the overall latent effort present in each iterative cycle. The other is fabrication, or 'compilation' as it is called in the software development workflow. Software engineering is by far the fastest in this regard. At any point the programmer may elect to compile and run their code with very little marginal cost. The tools for compiling software are fast, so feedback is immediate. Electrical engineering is slower than software, but still relatively rapid. A circuit design is created in the computer and then sent out to a 'board house', where it is fabricated into a printed circuit board (PCB) and mailed back. The engineer then populates the PCB with components such as resistors, capacitors, connectors, and integrated circuits. Depending on what you pay, fabrication might take anywhere from a few days to a few weeks. In both software and electronics, the process of building a design into an executable object (be it code on a computer or electronics in the physical environment) is a fairly generalized process. The programmer doesn't normally need to worry about how their code is compiled; so long as their syntax is valid, mathematics guarantees that it can be converted into machine code. When designing circuit boards, some care does need to be taken in the layout of traces such that the etching process is able to faithfully reproduce the design. But fortunately the rules are straightforward and only one fabrication process must be considered. Not so with mechanical engineering. A wide variety of fabrication processes are available to the designer, each with its own limitations and affordances.

Design and manufacturing are thus (at the moment still) tightly coupled, which loads down the design process. And compiling physical objects is not cheap and not (yet) fast.

The cost of making a mistake tends to push mechanical engineering's iterative cycles far into the realm of intelligent design.

Latent effort introduces a phase lag (to borrow a controls term) between goal and result. If the overall design process were a ship, phase lag would be the delay between when a heading is set and when the ship assumes its new course. Large phase lags put the ship at risk of missing its destination, and make it difficult to track a rapidly shifting course (as often occurs when creating something new). Most important to our aspirations for a clay world, however, is that phase lags have the effect of decoupling our actions from our senses. What good is malleability when the actions of our fingers and the sensation they generate are separated by great temporal distances?

There is nothing fundamentally necessary about latent effort. It is as much a fact of life for us as darkness was to the early humans before they invented fire.

7) We define aesthetics as morals for design; the opinion of the designer regarding what is right and what is wrong.

Tolerance and Precision; Satisficing and Maximizing[8]

One of the oldest standing bridges in the world is the Anji Bridge located in China and built in the year 6057. The cynic in us might use this as a counterpoint highlighting the erosion of craftsmanship in modern times. How is it that technology from the early 600BC has outlasted many a more recent structure? Did the inhabitants of this ancient time care more than we do? There is allure to the notion that they cared so deeply about their legacy. While we may never know why they constructed a bridge hearty enough to last 1400 years, we can be certain that the predictive ability of engineers today is far superior to that possessed by the designers of the Anji Bridge. Perhaps their bridge has lasted so long simply because they weren't able to be certain that anything weaker would last even 50 years.

With every attempt to make something work as we hope comes the problem's sensitivity to the precision of our intervention. In order for any design activity to be successful, the precision with which a solution can be executed must fall within the tolerance band of the problem it addresses. The gyroscopes used in spacecraft's navigation systems must be incredibly accurate in order to function properly. Whereas the exact thickness of the shelves of a bookcase have little bearing on its structural stability. The predictive powers of engineering allow us to optimize a design because they increase the precision with which we can predict the effects of our choices. When designing spacecraft this maximization becomes a valuable tool. However, with the tools available today, maximization can be time-consuming and tedious. Gestural design thrives on challenges whose tolerance is relatively high, allowing a commensurately low precision to the solution.

8) The term satisficing was first introduced by Herbert Simon in his 1956 paper 'Rational Choice and the Structure of the Environment.' A more recent (2002) paper 'Maximizing Versus Satisficing: Happiness Is a Matter of Choice'by Barry Schwartz and Andrew Ward found higher levels of happiness and other positive traits in individuals who chose to satisfice rather than maximize.

On Open Source Hardware

There has been brewing what many term the open source hardware movement. The 'open source' of 'open source hardware' is borrowed from the similarly named software movement, where it has a very pragmatic meaning. Raw computer code – the low-level instructions which orchestrate the operation of computing machinery – is quite impractical for us humans to write directly. High-level languages like C++ and Python allow us to focus on the logic of what we want to accomplish without becoming bogged down with implementation details. A tool called a compiler then transforms our easy-to-write source code into a much longer series of instructions matched to the hardware of the computer. In order to make changes to the program, one would modify the source code and then recompile; attempting to modify the compiled binary program is like trying to chip away at rock with your fingernails.

As digital fabrication tools become ubiquitous, a workflow which once was reserved for software is increasingly being applied to physical matter. No more will we cobble together pieces of wood purchased at the hardware store into a form which resembles the set of shelves we desire. Rather, we will go to a website that asks a few questions like how many shelves we want and the overall dimensions of the set. A plan will then be automatically generated and sent to a computer-controlled router, which will fabricate from plywood all of the parts for us to assemble according to the numbers conveniently etched on each piece. What if we later want to add an extra shelf? Do we modify the existing shelves (as we might do today), or do we change the design and then recompile as is done in software?

‘Open source’ means that something is being made available in a form which can be modified rather than just used. Implied, however, is the notion of a specific workflow: program -> compile -> execute. The issue with applying the prefix ‘open source’ to hardware isn’t that this workflow doesn’t fit; tantalizingly, it does. The problem is that this workflow is overly restrictive and excludes a richness of what is possible with real physical matter. As soon as we think of hardware as following the pattern of source-code, we give up our ability to interact with it directly.

Interacting with physical matter through a layer of abstraction – which bares more clearly the logic behind its design – has many benefits. So does an automated way of constructing objects far too complex or too repetitive to fabricate by hand. We do not advocate returning to the stone age. But it is clear that a better impedance match must be created between our brains and the objects which surround us if humanity is to continue to feel the sense of joy and resonance once intrinsic in the process of making.

We demand new tools and new aesthetics towards this end.

Towards Gestural Design

Gestural design is a low-impedance path for energy and information to flow bi-directionally between our minds and our environment. Necessary (but not sufficient) to this ideal are tools which can properly adapt us to our work. The analogy we draw between tools and transformers informs us that tools have inertia of their own. A gearbox, even in the absence of a load, absorbs some energy in its spinning mass. Many of our tools do indeed make hard tasks feel soft. A computer-controlled gantry router, for example, can shape plywood to mimic our intentions within a thousandth of an inch. Similar results would be challenging to achieve using hand tools. Where most modern tools fail is in the effort they absorb before outputting useful work. To build a rudimentary set of shelves by hand is a task which can be accomplished nearly as rapidly as the design can be conceived. But to fabricate shelving where each component is accurate to the degree de-facto produced by the gantry router is an all-day endeavor. First the design of the shelves needs to be expressed to the computer. Then each individual component must be broken out and composited onto a flat pattern. A tool path is generated, verified, and finally run on the machine. Because multiple pieces of software are involved in this workflow, there is a high degree of knowledge absorbed by the tool-chain alongside much latent effort. In this example, the inertia of the tool prevents us from operating at the speed of our thought, thus presenting a severe impediment to rapid interplay between our minds, hands, and environment.

If tools remain as massive in the future as they are today, the only hope for gestural design is in a change of aesthetics. By aesthetics we mean the morals which dictate what is right and what is wrong when it comes to design. (To view aesthetics as stylistic opinion undervalues its importance.) Beauty must be derived from the clarity of a concept rather than the perfection of details. Few details are preferable to many well-resolved details. Error-tolerant designs are preferable to precision fabrication. Objects are more than state functions; the path they have taken, and will take, matters.

The tools of the future will facilitate gestural design. We will have tools which are more tightly coupled to our computers, and we will have computers which are more tightly coupled to our tools[9]. The act of design should be synchronous with fabrication. Serendipity must once again reclaim its throne.

9) See ‘Position-Correcting Tools for 2D Digital Fabrication’ by Alec Rivers, Ilan Moyer, and Frédo Durand.

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And **Melissa Rothstein**, whose existence reminds me.

Irreversible ↔	Reversible
Unique ↔	Repetition
Low Integration ↔	Highly Integrated
Modular ↔	Monolithic
Sculptural ↔	Geometric
Low Order Approximation ↔	High Order Approximation
Low Embodied Design Logic ↔	High Embodied Design Logic
Low Design Integrity ↔	High Design Integrity
Disposable ↔	Durable
Open Box ↔	Closed Box
Creative Solutions ↔	Obvious Solutions
Poor Design Logic Capture ↔	Good Design Logic Capture
Poor Geometric Caputure ↔	Good Geometric Capture
Poor Incidental Documentation ↔	Good Incidental Documentation
Low Fidelity Replication ↔	High Fidelity Replication
Easy Replication ↔	Tedious Replication
Low Design Accesibility ↔	High Design Accesibility