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Small Artifacts – Big Technologies:

The Power of Imperfect Principles

SMALL ARTIFACTS – BIG TECHNOLOGIES:

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ABSTRACT

The computer IC is the heart of the information and telecommunication technology. It is a tiny artifact, but with incredible organizing powers. We use this physical artifact as the location for studying central problems of the knowledge economy.

First, the paper describes the history of chip design and the emergence of the technological community involved in designing and manufacturing computer chips. The community is structured in a way that reflects the underlying physical nature silicon and the numerous other materials and chemicals involved. But it also reflects the human agency of defining new projects, of visioning the liberation from atoms, of committing to travel many detours in the labyrinths of development, and of perceiving and exploring the affordance that new technologies hide.

Some of these characteristics are analyzed empirically in a case study of designing a chip for a digitalized hearing instrument. It is found that technological progress is not hindered, but rather aided by the use of imperfect principles, abstractions and representations of reality. The power of such imperfections is discussed and generalized.

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SMALL ARTIFACTS – BIG TECHNOLOGIES:

The Power of Imperfect Principles

> To see the World in a Grain of Sand,
> And a Heaven in a Wild Flower,
> Hold Infinity in the Palm of Your Hand,
> And Eternity in an Hour"
> (William Blake, *Auguries of Innocence*, quoted from
> Bateson, 2000)

INTRODUCTION: THE DIGITALIZATION OF SOCIETY

This paper attempts to see the world of information technology and product development in the tiny, technical artifact, the Integrated Circuit (IC) – for convenience also referred to as chips. Chips are the heart of the all the numerous computers in modern society. The paper is an account of the complexities of modern technology, but also a theory about the ways in which aggregate complexity is produced by the systematic application of very simple principles of distinction and organization; and about the ways in which the functionality and performativity at the aggregate level depend on the ingenious management of the integrity of these simple principles.

We start with a very brief account of the history of IC design and the building of the vast community of diverse actors involved in designing and manufacturing of ICs. Next, we analyze a specific case of product development, which revolves around the design of a specialized chip. From this case we deduce some patterns of behavior and management that apparently led to success in the specific case, and which may explain the success in general of the computerization and digitalization of organizations and society. The successes are less surprising than the principles and behavioral patterns that we describe. This leads to speculations on how to conceptualize the managerial and organizational challenges in connection with the development of new technology and the design of new chips.

The interest in a material artifact, in the present case the chip, may seem a little old-fashioned. It is the current understanding that physical artifacts become less and less important, while symbolic artifacts become more and more important. Expressed in a more fashionable terminology, we move from atoms to bits,

> *"World trade has traditionally consisted of exchanging atoms. ... [W]e were shipping a large, heavy, and inert mass, slowly, painfully, and expensively, across thousands of miles, over a period of many days. When you go through customs you declare your atoms, not your bits. ... This is changing rapidly. The methodical movement of recorded music as pieces of plastic, like the slow human handling of most information in the form of books, magazines, newspapers, and videocassettes, is about to become the instantaneous and inexpensive transfer of electronic data that move at the speed of light. In this form, the information can become universally accessible. ... The change from atoms to bits is irrevocable and unstoppable" (p.4)*
> (Negroponte, 1995)

True it is that digitalization is ubiquitous. More and more things are put into digital form for use and transportation by computers. The following illustration indicates the possibilities and promises of exchanging bits for atoms:

> *In 2002 the Danish Government allocated a large sum of money to the digitalization of the Danish cultural heritage![1] The political ambition is to make this cultural heritage accessible to the public at large from a home computer.*

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[1] http://www.kum.dk/sw5379.asp. Press release from Ministry of Culture, 9 Januar 2003.

It saves the Danes a good bit of traveling, in space and time, when they want to get into contact with their cultural roots. In the terminology of e.g. Deleuze and Latour, all these distant histories and achievements are *folded* into a technical devise that enables people to collect information, to explore their imaginations, and to develop new appreciations and insights (Latour, 2002). Long ago our forefathers toiled with heavy stones to properly bury one of their kings, leaving the dolmen in the farmers' way today. Without much toil we can now bring these stones and stories home – in virtual form. Exotic history and cultivated citizens – just a few keystrokes away!

While we will not be concerned with the question whether such promises of the digitalization are actually kept, it may be worthwhile to explicate an assumption about the relationship between bits and atoms. In the words of Latour, *technology is half instrumentation, half "affordance"* (Gibson, 1986; Latour, 2002) – it issues permissions and promises which are grasped and enacted, and which eventually lead to new ends and new functions, some undoubtedly more valuable and significant than others. Technology cannot have worth as bits without some atoms somewhere. It is the combination of atoms and bits that should concern and fascinate us. We may be more interested in the affordance and the bits, but these interests are folded into material artifacts. When Latour equips people with a hammer, their "projects" change because of "… the flux of possibilities that they are suddenly able to envisage" (Latour, 2002). The atoms generate the bits and their relevance by fostering new visions and goals. When we become equipped with computers and digitalized cultural heritage, we possibly may develop an urge to visit our cultural roots, even their material form at the museum – and undoubtedly to digitize even more things. Preferences and projects emerge endogenously, closely related to the perception of the promises and permissions that the new technology holds (Cyert & March, 1992; March & Simon, 1993; March, 1999).

True it is, however, that we often can allow ourselves to forget about the atoms – to pretend that only bits are important. However, to do so without negative consequences depends on material artifacts – on the atoms being successfully disciplined. This is what chip design is all about, disciplining the "atoms" in a way that make them allies in whatever project we set out to accomplish.

Thus, there is nothing paradoxical in studying the nature of the information society and the knowledge economy in the arrangement of atoms in chips. The perspective we adopt in analyzing the chip design and production highlights the heterogeneous temporalities, spaces and actors hidden in the physical artifact and ready to be unfolded. In Latour's words, "There is nothing less local, less contemporary, less brutal than a hammer, as soon as one begins to unfold what it sets in motion..." (Latour, 2002): p. 249). What is true of hammers is certainly true of ICs. They are narrow issues when looked upon as final tools and dead physical objects. They are entries to a past and current history when we treat them as a vantage point from which we can appreciate the multiple processes, interests, compromises and serendipity that go into making and exploiting them.

Thus, we will try to get to the "big picture" of organizing and managing efforts in the knowledge economy by unfolding this tiny material artifact – searching the artifact for traces and marks of these efforts and aspirations. And we will start from the very beginning by consulting Boolean logic and the physical nature of silicon.

THE ARTIFACT, THE COMPUTER IC

In most accounts, Claude Shannon (1916-2001) is the central figure in the invention of the modern computer. In the 1930's he worked on Vannevar Bush's mechanical computing device, the Differential Analyser. This device was cumbersome to work with because every change of input involved a reconfiguration of all the mechanical gears etc. Having been trained in Boolean algebra as an undergraduate, he somehow came to think of the parallel between telephone switch circuits and symbolic logics. He made the translation from "on" and "off" to "true" and "false" – and eventually provided the mathematical foundation for the engineering of circuitry lay out. Information was relieved of any content and meaning – semantics is simply not relevant to the engineering problem, which was about expressing information in quantitative form. Complex messages consist of strictly logical aggregation of on-or-off bits (the acronym of Binary Digits) that conventionally are bundled into Bytes (8-bits combinations). Letters and signs are represented by bytes, words by combinations of bytes, sentences by combinations of combinations of bytes, and so on and so forth.

The history of the development of the IC is a repeated celebration of such simplicity. It is from the extension of the same basic principles that the complexity and nuances at the aggregate level emerge. No matter how complex computers and their applications become, the foundation is still the Boolean logic that allows "everything" to be represented by bits and bytes. Possibly all you need to understand is three types of logical gates. Inspired combinations of such logical gates will eventually capture everything under the Sun.

Around the same time as Shannon made his contribution to the logical foundation of the IC, W.H. Brattain accidentally discovered that silicon becomes a conductor when water condenses

on it. In its pure form, silicon is an insulator. As it turned out, it was the "pollution" with water

that changed its conducting character. The next many years of development was focused on

making the pollution "effective" and the conductivity controllable. That involved, on the one

hand, making the silicon purer and, on the other hand, implanting impurity in the form of ions of

e.g. arsenic and gallium that allowed the current to pass on certain controllable conditions – to

turn on or off the electricity. Eventually, the transistor, i.e. the physical embodiment of the

logical gate mentioned above, was developed.

With the advancement of production technology, it is today possible to produce transistors

reliably and inexpensively. The packing of thousands of transistors on a piece of silicon,

patterned according to a logical circuitry layout, embodies the modern IC. Its complexity is

awesome, yet:

> *The fundamental principles are surprisingly simple. The miracle is the constant*
>
> *refinement of those principles to the point where, today, tens of millions of*
>
> *transistors can be inexpensively formed onto a single IC.* [2]

E.g. the INTEL Pentium 4 holds no less than 42 million transistors. Even so, it is the same basic

principles of the transistors and the same three fundamental types of gates that still are producing

such technical progress.

In summary, the complexities of modern computers have a very simple and common foundation:

- It is based on a very simple logic, one that distinguishes between true and false conditions
  (Boolean logic).

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[2] www.electronics.howstuffworks.com/diode.htm p. 5.

- The logic is translated into silicon, one of the most common elements on the Earth – the main element in e.g. sand.

- The vast increase in efficiency and applicability is a result of a systematic extension of the same principles – more transistors, finer masks, purer silicon, etc.

Like a standard-sized brick can produce wonderfully diverse patterns and complex buildings with a bit of architectural ingenuity and craftsmanship, so can a logical principle and its implementation in the form of transistors seemingly lead to an infinite number of highly complex and advanced applications.

THE IC COMMUNITY

Now we turn to the technological community that designs and produces the IC to specific applications. The abovementioned principle of simplicity behind the complexity of the artifact we recognize again for the organization of the value chain. It consists of a bewildering number of points of specialization, but each point in the chain is a fairly simple *action net* (Czarniawska, 2002; Czarniawska, 1997).

E.g., in the one end of the value chain we find companies specializing in *the crystal pulling* to produce the purest forms of silicon – and we have other companies specializing in producing *the machines pulling the crystals*. Further down the value chain we have companies specializing in producing various *chemicals* which will enhance the insulation. And we have the big manufacturing *fabs* (with the well-known brand names) which translate the circuit design into silicon and encapsulate them.

The mentioned points of specialization are just a few examples of the literally hundreds of points, each with further networks of specialized suppliers of materials, tools, and machinery. Most of the structural building blocks are rather small action nets. As an extreme example, we found a point of specialization in the manufacturing of machines that apply the welding substrate when the IC is attached to the circuit board. Two suppliers of such machines alone share 80-90% of the world market.

The picture that emerges is again one of *aggregate complexity*. Each building block is fairly manageable in terms of number of competitors, product variants, technological agendas etc. However, when such building blocks combine in thousands, we face a perplexing structural proliferation, an extreme degree of specialization and a monumental division of labor. It is not difficult to understand what drives this process of proliferation. Take the above-mentioned machines for applying welding substrate as an example. The number of legs and contacts that connect the IC to the circuit board has risen rapidly over the years, while at the same time the IC size has shrunk. Some years back welding substrate was applied manually, but since growing ambitions in the design of ICs also generated a need for incredible precision in this tiny step – a degree of precision that could not be met by humans – the development of "welding substrate application" tools and machines became a matter of necessity for exploiting the technical advances in practice.

Simple Principles of Coordination and Organization

A huge number of actors and technical disciplines collaborate in designing and producing the IC and in increasing its efficiency and performativity at a rapid pace.[3] All knowledge domains and participants seem perfectly aligned, making one suspect that an elaborate social structure must be in place to coordinate the multitude of activities. However, it appears that the system is more like a spontaneous order (Hayek, 1948; Kirzner, 1992) – or as Weick would have it, a collective that behaves *as if* it was organized and coordinated centrally (Weick & Roberts, 2001). How is it possible to achieve high levels of coordination *spontaneously*.

The main explanation is *division of knowledge*. According to Hayek (1948), civilization thrives on such a division of knowledge (Kirzner, 1992). Each action net relates to other action nets on a basis of familiarity, not knowledge. Division of knowledge is one of the most celebrated features of modern civilization because it allows us all to concentrate on adding knowledge to knowledge, i.e. building *our own* knowledge on top of the knowledge of everybody else – which, according to (Drucker, 1993) is the only, or at least the most important value creating operation. We know what our computer can do – and under which conditions it will do it. It really doesn't matter that we are at a complete loss when asked to explain why and how it works. In a similar manner (except perhaps at a somewhat higher level of understanding) the various actors may engage in dedicated development work within their local action net. If they can improve the performativity in one or the other direction, others will see it as a permission to add their own

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[3] Even within this spontaneous order, the rate of innovation is enormous. The best indication is Moore's law that states that an IC's number of transistors will double every 18 months. The law is still valid according to empirical evidence!

knowledge and ingenuity in exploiting the new opportunity. Thus, for example, the development

of new lithography techniques that allow vastly reduced photo masks and the etching of many

more transistors on the IC can take place at a local point in the value chain without coordination

with everybody else. When the new technique has been developed, other action nets may

perceive new possibilities to be explored and exploited. However, even if the affordance of the

new lithography technique is not perceived and exploited in the short run, this does not threaten

the alignment and coordination of the actors in the value chain. Thus, the relationships in the

knowledge economy are more dominated by affordance than by dependencies, and the need for

coordination (beyond what is already built into the structure of the value chain) is minimal.

This raises the question how we may understand the structure of the value chain. Having already

characterized it as a spontaneous order, we are not searching for somebody who designed the

value chain. We are searching for evolutionary principles that produced the current structure as

an outcome. One such principle is the sequential application of technical ingenuity.

Technological development can be pictures as an exploration of a labyrinth, with the repeated

encounter of impasses.

> *Ingenuity begins with Daedalus, prince of the labyrinth, that is, with the unexpected*
>
> *branching-out which at first distances us from the goal. (Frontisi-Ducroux, 1975).*
>
> *When we say there is a technical problem to resolve, we precisely wish to introduce*
>
> *the addressee to the detour, to the labyrinth that he will have to confront before*
>
> *pursuing his initial objectives.* (Latour, 2002)

Detours, technical problems, or as Ciborra (2002) calls it, "reverse salients" hinder progress, but

also stimulate effort, ingenuity and creativity. When such efforts are successful new knowledge

emerges, new possibilities for specialization arise, and new divisions of knowledge and structural

proliferation are occasioned. Each innovation creates a challenge for other, often neighboring action nets. Before the lithographic innovation can be exploited new insulating chemicals and new machines for connecting transistors may need to be invented. Such impasses may slow down progress, but will also greatly direct and motivate the ingenuity of other members of the IC community. The mobilization of new types of knowledge, and the structural alignment of new types of experts, is the result of repeatedly encountering impasses, obstacles, and technical problems. Each exploration of the labyrinth will produce new impasses, obstacles, and problems.

The ways in which such impasses, obstacles, and problems are determined and defined in the course of technological development will be analyzed in details in a case study of hearing instruments. In sum, we see the value chain of the chip as a perfect illustration of the knowledge economy. The division of knowledge is astonishing; the structure has arisen gradually, as a proliferation of points of specialization, in response to the encounter of technical impasses at each and every turn in the labyrinth. Each successful victory over a technical obstacle has opened new venues for progress and new innovations. Thus, the community is structured in a way that reflects the underlying physical nature silicon and the numerous other materials and chemicals involved. It also reflects the human agency of defining new projects, of visioning the liberation from atoms, of committing to travel many detours in the labyrinth of development, and of perceiving and exploring the affordance that every new impasse potentially hides.

COMPUTERIZED HEARING INSTRUMENTS: A CASE STORY[4]

1995 was the year when hearing instruments turned into a computer. It took four years of concentrated development work and more than ten years of audiological research to achieve this. (Oticon Annual Report 1995 – our translation)

This was the jubilant announcement of major technological breakthrough by the Danish manufacturer, Oticon, who had hitherto been famous mainly for its exotic 'spaghetti organization' (Peters, 1992). The new hearing instrument with a 'digital audio processor' was named DigiFocus.

DigiFocus was meant to *improve the quality of life* for the hearing impaired population. The needs of this population were construed in ways that translated into three specific requirements that the new hearing instrument aimed to fulfill:

- **Miniaturization** – to satisfy aesthetic demands

- **High fidelity** sound reproduction – to satisfy the functional demands in often chaotically changing sound and noise environments. Since hearing impairment is highly idiosyncratic, this requirement included a need for adapting the instrument to the individual user.

- **Usability** – to satisfy the need for forgetting the instrument (and the hearing impairment) in daily life, including avoiding a too often recharging of batteries and an automatic adjustment of volume etc.

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[4] Our account is based primarily on publicly available material, e.g. annual reports and (Pedersen. The Genesis of a Digital Hearing Instrument. Hearing Instruments [March], 38-39. 1996.). In connection with another study (authors) we interviewed a number of people inside and outside Oticon who were involved in the DigiFocus project. The logical structure of the problem presentation is documented in this material, but the data collection does not allow us to claim detailed insights into the particular processes, the intentions of the actors, and the historical contingencies that impinged upon the development process.
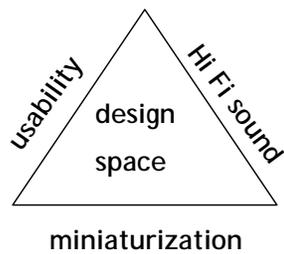
Figure 1: The Design Space for Hearing Instruments

The exploration of this design space, which ultimately materialized in the form of the DigiFocus, was in many ways unpredictable and indirect. The project team continued to hit upon technical problems that needed to be solved before further progress could be made. On one occasion, one that will be the focal theme of this case account, the project got sidetracked to a quite foreign place.

Some researchers have likened the process of technology development to moving around in a labyrinth (Latour, 2002). At each turn, new obstacles appear that block the direct way to the goal. Solving the problems requires you to take a detour that initially distances you further from the goal, but which eventually allows you to make progress.

We will describe the labyrinth in some detail. We will also describe the competencies and strategies that enabled Oticon, with ingenuity and luck, to find its way in the labyrinth towards the goal.

The Technical Obstacles of Hearing Instrument Design

To put a small computer into a hearing instrument was the overarching concept of DigiFocus. The heart of a computer is a chip. The high performance of the chip was critical for achieving Hi

Fi sound reproduction. Computer chips operate on electricity. In the case of hearing instruments, batteries were (and so far are) the only available source of electricity.

Increasing the quality of the sound reproduction could be translated into an increasing number of operations that the chip needed to perform. E.g. traditionally, compression is done in three frequency bands, but DigiFocus was conceived to compress in seven bands. The more operations required of the chip, the higher its power consumption. Everything else being equal, the increase in sound reproduction quality could be translated into a need for higher battery capacity.

However, the capacity of the batteries is positively correlated to their size. Simply adding capacity by increasing battery size was not an option in view of the miniaturization constraint. Simply reducing capacity by increasing the frequency of recharging batteries was not an option in view of the usability constraint. An adequately small battery, with a correspondingly small capacity, was not an option because of the Hi Fi sound reproduction constraint. The only logical way out of this design impasse was *to invent* a chip with lower energy consumption.

Lowering the energy consumption of a chip can be achieved by lowering its voltage. At the time, the standard voltage in all modern electronic equipment was 5 volt, but DigiFocus became envisioned to be equipped with a 1-volt chip, which would reduce the power consumption to 1/25! Oticon had never done it before, and existing design tools and libraries were of little use for the chip designers in arriving at a functional design. Work had to be done at the transistor level all along, which made the design job very complex. At the time of taking this turn in the labyrinth it was not at all certain whether such a detour would lead to success, i.e. that such a functional design could be made within the time parameters of the project. This became the more uncertain when further obstacles were encountered.

While reducing the power consumption, reducing the voltage has also less fortunate implications. First of all, it reduces the speed of the chip, which translates directly into a loss in performance. The strategy of lowering the chip's voltage might prove self-defeating unless the chip designers were able to increase the efficiency of the chip itself. Many new design features were invented and built into the chip, e.g. in the form of new ways of parallel processing. However, immediately the choice of a 1-volt chip simply redefined the problem from one of providing sufficient battery power to one of increasing the efficiency of the chip, i.e. to perform more functions within a given capacity.

The choice of a lower voltage solution had other implications. With a 1-volt chip the whole spectrum of sound (in terms of frequencies) has to be represented on a vastly reduced scale. This would require a level of precision that was unattainable with the envisioned chip. Thus, the development of DigiFocus arrived at a new impasse. Saving energy by lowering the voltage of the chip not only slowed it down; in the context of hearing instruments it also added new and unattainable processing requirements. It seemed that this strategy led from one impasse to another even worse impasse.

Logically, the need for precision would be relaxed if not all frequencies needed to be represented on the 1-volt scale, i.e. if some frequencies could be skipped. The implied logic is heretic, however, because according to commonsense that would also reduce the quality in sound reproduction. Nonetheless, the question was framed in this way to escape the impasse: can some frequencies be skipped without the human ear noticing a loss of sound reproduction quality – and if so, *which* frequencies could be skipped?

This turn in the labyrinth was dramatic in a different way than the previous ones had been. It shipped the problem out of the hands of Oticon's own experts in chip design and electro

acoustics, and into the hands of experts in psychoacoustics. Perceived sound quality is highly

subjective, and psychoacoustics conducts experiments on human beings to collect data on their

perceptions. Thus, the problem was transported not only to a foreign university where the

experiments were conducted over several years; it was also transported to a foreign knowledge

domain – foreign in terms of both expertise and methodology.

Eventually, the psychoacoustics experts provided the IC designers with the algorithms and

specifications they needed to reduce the replication of frequencies. With this break-through of

the hitherto technical impasse, their chip design proved feasible and the DigiFocus became a

functional hearing instrument and an immediate commercial success.

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This is far from the whole story, and importantly, it is *our* story: our reconstruction of the logic

behind the impasses encountered along the way – and the logic behind the detours of developing

a hearing instrument. It cannot be claimed that these logical steps correspond to the episodic

events in the empirical process. Furthermore, it cannot be claimed to correspond to the

experience and current memory of the involved experts. In is quite possible, even likely, that our

imputation of an underlying logic in the detours was experienced as annoying obstacles and

unnecessary delays. Thus, we make no secret of the fact that this account is a logical

reconstruction – and clearly a simplification of the actual empirical process. We cannot claim

more than that the impasses described were real (whether or not they were attended to as such),

and that the exploration of the labyrinth *might* have happened as we described it.

Case Analysis: The Construction of the Labyrinth

The critical step in our logical reconstruction of the development process of DigiFocus is the development of the algorithm for skipping frequencies – and by the same token, the inclusion of psycho-acoustical experts. They were mobilized on the paradoxical idea that frequencies could be eliminated without a loss in reproduction quality. The chip designers were mobilized on the equally paradoxical idea that the number of operations could be increased with a slower chip. Both were successful in finding a solution to the problem. Had they been unsuccessful, our specific reconstruction of the case would have been changed, but the logic would have remained the same. The logic is one of defining labyrinths and shifting around impasses for various experts to circumvent. The process could be conceptualized as one of finding new ways of *presenting* problems, rather than straightforward searches for solutions. As such, the problem could be seen to have the character of an "insight problem" (Simon, 1999).

New ways of presenting a problem seems to have much organizing power, but in a different manner than most theories assume. Most theories about new product development focus on a project team with shared structural capital, a common understanding of the mission and problem, a high degree of coordination and an architectural design that is frozen from the outset. Our picture is different. Little communication and mutual understanding were required for the two domains to establish order.[5] Simple ideas stated in an ordinary language that even we, as lay

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[5] There is no doubt that considerably more social interaction and communication took place across the domains of knowledge. Some of this communication had no doubt the function of creating mutual trust and respect. We do not propose to cut out such forms of communication. In the present context, however, our aim is to understand how little communication is required for transmitting the knowledge from one domain to the other.

readers, understand, and awaiting an answer in a less simple, yet operational language formed

the point of tangency. And while we cannot accept that the quantitative form of information (the

algorithm) was without content and meaning, we can safely claim that it had highly different and

local content and meaning. The algorithm acquired the character of a boundary object. A

boundary object has an identity, but it means quite different things to different communities.

Visually, it is exactly the point of tangency between communities or knowledge domains. The

same thing (the algorithm) meant less instructions and higher speed to IC designers, less power

consumption to the electrical engineers, and a whole new paradigm for studying the human ear

and the perception of sound to the psycho-acoustics experts. To the sales people it meant a

highly convincing argument (even scientifically accountable) for introducing a revolutionary

first-mover product in a very profitable segment of the market; to the production people it meant

new alliances with highly specialized IC fabs. The organizing potency of a boundary object is the

number of contexts in which it is enacted and rendered meaningful. The idea of less accuracy in

reproducing hi-fi quality was fuzzy, yet meaningful. It gave the psychoacoustics experts the

license to work on a new and enlarging set of problems. When they returned with a 'solution' in

the form of the algorithm, this solution was immediately useful to the chip designers. The chip

designers did not need to understand the first thing about psychoacoustics.[6] They were not

dependent on the intentions and premises that these foreign experts worked on. They might as

well have read the algorithms in a book, had this book existed, which it did not, of course. They

imagined that such a book could be written and found somebody to write it for them.

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[6] In fact, they probably did know quite a lot. Also, they probably communicated more with the psychoacoustics

experts in Sweden that we have described here. But the chip designers' ability to add knowledge to the knowledge

of the psychoacoustics experts would seem not to hinge on such communication and insights.

Likewise, the psychoacoustics experts did not need to know anything about chip design, power-consumption and the aesthetic demands of customers. They were handed a problem that made immediate sense within their specialized and isolated knowledge domain. They responded to the problem not because of an appreciation of its significance to others, but because of an appreciation of its significance to their own domain. They produced a solution in a form that did not reflect the needs of the chip designers, but that reflected their own new way of knowing. It was "readable" for the chip designers, not because the psycho-acoustical experts tried to communicate their insights, but because the solution was packaged in an algorithm that could be implemented as a black-box.

It is important to remember that there was nothing inevitable about the psycho-acoustics experts' discovery of an algorithm; nor was there anything inevitable about the chip designers' formulation of the impasse in terms of a reduction of the number for frequencies reproduced. It was necessarily a tentative formulation of an insight problem. History could have turned out quite differently. Clearly, they could have discarded the feasibility of a 1-volt chip from the beginning, in which case they might never have involved the psycho-acoustical experts – at least not in the central role in which they actually ended up. In hindsight we know that the strategy was feasible and productive, but there is no guarantee that feasible and productive strategies are perceived and adopted. The labyrinth could have been conceived differently, charging other experts with the task of devising the break-through.

Summary

The success of the OTICON was manifest. We can safely ascribe this success to the ingenuity of the involved designers and experts. However, had the same strategy not resulted in a feasible

hearing instrument it would probably have been said to be naïve or wrong. In fact, for a very long time the successful outcome was in serious doubt. Furthermore, we have no way of knowing if a different strategy would have produced an even more productive result.

Thus, we cannot claim that the same strategy would lead to similar break-through results, were it repeated a second time. And if the same strategy led to fiasco, we could not claim that the strategy was wrong. Many factors will contribute to the eventual outcome, good or bad. We cannot possibly control for all these factors – nor can the experts and managers in practice. There is nothing deterministic about technology and product development.

Yet, the strategy which we will characterize shortly, proved to be a feasible one. It provided a context, a labyrinth, which gave new perspectives on inherent affordances and which led to many types of local exploration. If management was involved, it was involved in arranging the context in such a way that impasses were considered challenging and worthwhile. Management, and the chip designers, had little competence for giving advice to the psycho-acoustical experts on how to solve the puzzle. They created the context, defined the challenge, provided the incentives, and awaited the experts to perceive the challenge and pursue the ideas. Thus, the *management* of technology is half instrumentation, half affordance! It fosters ingenuity as much as it practices it. It motivates as much as it directs. It depends on the outcome of the process as much as the outcome depends on it. It legitimizes exploration and possibly futility, as much as it requests exploitation and efficiency. It poses paradoxical questions as much as it aims at clearly translatable answers. It depends much on the ingenious enactment of what might easily be portrayed as paradoxical and uninformed requests.

According to most standards, such management would seem highly imperfect. It would seem to relinquish all managerial control – to accept the fate control of (in this case) some distant

psycho-acoustical experts. We think we know from the case study that on this occasion it actually worked. But perhaps the most serious erosion of control is the inability to evaluate outcomes and to learn from experience in the knowledge economy characterized by an elaborate division of knowledge. That issue we will discuss in the next section.

THE EROSION OF CONTROL

Adding knowledge to knowledge implies that the knowledge of others is black-boxed and used as tools in our own projects. It gives us immense power, as when the chip designers could implement the algorithm of many years of psycho-acoustical experimentation. And at the same time, the possibility for exploiting the power of the tools implies a concurrent erosion of control, the control of being able to evaluate the solutions and services that are provided by the tool or the other experts. In the case described above, we have a clear appreciation of the functional adequacy of the algorithm. However, we (and the chip designers) have no way of knowing whether the algorithm might be much stricter, allowing an even higher performance of the hearing instrument.

The set of issues find a parallel in the discussion of the use of design tools for chip design. In another study of ASIC design [author] we interviewed designers about the experience of having a mediated access to reality by using design tools.

> *There is a tendency to satisfy the design tools. In most cases ASIC designers can hardly be said to be taking maximum advantage of the potential for high speed and low power consumption in the processor that is actually used in a specific application…*

Designers become isolated from the reality on the other side of the tool. [The tool]

says: Sure, you can specify whatever you want in the whole wide world. Then I – the

design tool – will build it for you. [But] You may get 100 gates [a proxy for the

number of transistors – authors' comments] instead of 16 for a given problem if the

design tool is allowed to decide.

The general story behind the seductive design tool is that it both permits and restricts. You can

book your own plane tickets, design your own living room, select the right school for your

children, or find a restaurant with a good hygienic reputation. In our case, you can ask distant

experts about the feasibility of skipping frequencies without loss of perceived sound quality.

However, the ability to operate in the knowledge economy is not match by an ability to critically

evaluate the result. You may feel vindicated by the outcomes, and feel certain of your own

ability or luck. You may appreciate the school you chose, without ever being able to check

whether other schools might have proven even better for your child.

The lesson from surrendering authority to the design tool or algorithms is not a clear-cut one. We

may recognize the inherent risk of operating at a level of familiarity. The Drucker argument of

value production by adding knowledge to knowledge faces its limits. Applying own knowledge

to the knowledge of others, with which one is familiar, but not knowledgeable, should be

celebrated as the hallmark of the division of knowledge in our modern civilization. It is the great

accomplishment of the knowledge economy that it allows so much focus and attention to be

devoted to people's own projects and explorations – the knowledge of all the others making such

a focus possible and attractive. We can do more and more things, and we can aspire to do even

more things. But we can critically assess and appreciate the outcomes less and less. There is an

inherent risk of becoming used to, even being *seduced to like* bad solutions. We may not realize

these costs, since our satisfaction is governed not by critical scrutiny, but by aspirations and/or common standards. Bad solutions are of course bad if they do not function at all. But they are still sorts of solutions as long as they function at some minimal level of efficiency. Solutions that are bad constitute type 2 problems (Hayek, 1948; Kirzner, 1992) and the costs are opportunity costs.

THE PERFORMATIVITY OF IMPERFECTIONS

It might be tempting to claim that bad ideas, as discussed above, rest on wrong or ambiguous ideas. But the example of chip design and manufacturing suggests that this is certainly not the case. Most of the development as we have described it is based on visions and abstractions that are clearly inaccurate or simply wrong. The most immediate example is the claim that we can model the physical reality of silicon on the model of Boolean logic. The model is elegant and elaborate but it is notoriously a poor representation of the physical reality. Consider the following observation by a chip designer,

> *The claim that we deal with a digital reality is not true. Of course, the physical reality is one of currents [of electrons] at different levels of intensity, higher or lower. But we have created an abstraction that says: we only need to distinguish between two states – one that we call 'off' and one that we call 'on'. This is an incredibly powerful abstraction. So instead of thinking in terms of continuous levels of currents when building a computer – a world so complex that you would never be able to build anything – we've got this abstraction that allows you to assume that the*

current is either off or on. But the physical reality is not like that. Designers tend to

forget this, and that can produce mistakes when the design is translated into silicon.[7]

A proxy, an abstraction that simplifies and translates all Nature's intricacies into two distinct states, is recognized as "incredibly powerful". It has enabled the community to design vastly complex chips and computers. However, at some point in the technological development, another truth will emerge. Nature is not digital; it is analogue, and much more difficult to model and designing analogue.

We need to understand the power of a simplified and inaccurate rendering of the physical reality, which we want to control and exploit. At some point, the simplicity and controllability will meet with the complexities and paradoxes of real life situations, just as the Boolean logic will meet the heedless electrons. Design at the sub-micron level threatens to bring us in a situation where we cannot determine whether the gate is open or closed. Thus, the success of the IC design lies in avoiding such situations.

The abstraction introduced by Shannon's logic was translated into a physical material, into silicon. It presumed a character of physical nature that was helpful, but incorrect. More and more labyrinths will have to be traveled to circumvent this problem, as ambitions for more and more transistors continue to grow. So far, other inventions have allowed the designers not to relax their ambitions to honor Moore's law. The problems have been defined, and the labyrinth has been designed ,in such a way that new inventions have extended the zone of validity of the abstraction.

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[7] Quoted from [authors].

It seems from the case, however, that the abstraction and simplification is not the problem, but the solution. The solution to increase the quality of the sound reproduction was a less perfect reproduction, not a more perfect reproduction. The quality of the outcome did not depend on the number of frequencies alone. It depended on the total constitution of the hearing instrument. A reduction of the number of frequencies allowed the chip designers and the electro engineers to accomplish things that vastly compensated for the imperfection of the frequencies reproduced. Furthermore, the human ear was demonstrated not to be able to perceive the increased inaccurateness. It doesn't matter if inputs (in terms of principles, models and abstractions) are correct. The pragmatic, and decisive criterion for assessing the quality relates not to the input, but to the outputs. If the inaccurateness can be controlled in terms of the effects on the outputs, a relaxation on the accuracy and perfection of inputs may provide the impetus to an exploration of many routes and paths of the labyrinth of technological development.

CONCLUSIONS

This paper has been a celebration of the several types of imperfection. The technological problems involved in designing and manufacturing computer chips have given an insight in problems and issues in the knowledge economy at large. The imperfections have been suggested to enable rather than endanger technological progress.

- The imperfection of the silicon (its pollution with ions of arsenic and gallium) gave it its semi-conducting character and thereby the possibility to embody logical gates.

- The inaccurate rendering of physical reality as being digital allowed the application of Boolean logic and the design of immensely complex IC architectures and applications.

- The interaction across the community of chip design and manufacturing based on familiarity rather than knowledge allowed the adding

knowledge to knowledge which produced a vast growth in technology and civilization.

- The impasses of developing the close to perfect hearing instrument were overcome by accepting an incomplete representation of sound frequencies.

- The strategy of technological development was portrayed as one of multiple detours, pursuing an indirect road towards the goal.

In many ways, all these examples challenge the conventional ways to defining the managerial role in the knowledge economy. We claimed above that technology management is half instrumentation, half affordance. But we come to conclude that it is probably more affordance than instrumentation. It seems to avoid providing efficient inputs and precise guidelines. Rather it stimulates search, imagination and the exploration of the labyrinth, very often by erecting impasses, rather than removing them. We don't know if that qualifies as good management, and if it doesn't, then the efficiency of an imperfectly managed community of chip design and manufacturing should not surprise us. Still it requires some kind of explanation. That seems to be the current impasse for the further development of the theory of technology management.

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