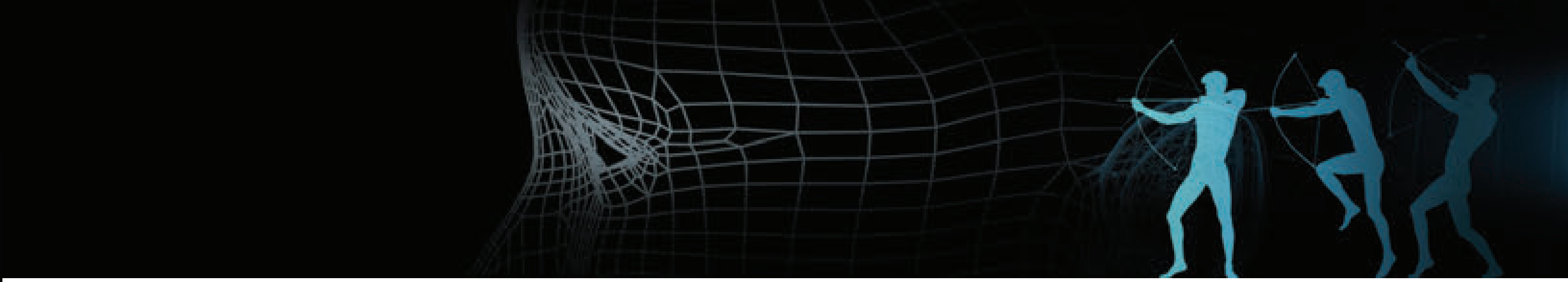
SPACE MAPPING



Have You Ever Wondered About The Engineer's Mysterious "Feel" For A Problem?

by **John Bandler**

Eureka Moment

"Come and look at this," Steve Chen said in 1993.

I still see him in the doorway, beckoning me, and I remember where his computer stood and how it was oriented as I leaned towards its screen seconds later for my first glimpse at the results of a novel approach to automated design, a technique that I believe encapsulates the engineer's mysterious "feel" for a problem—an issue that had dogged my 30-year immersion in the art and science of optimization for computer-oriented engineering design.

Why had this concept taken so long to reveal itself?

Back-Story

I recall two rebukes in the 1960s during my undergraduate years at Imperial College, London, that were influential in my brush with the engineer's feel for a problem. At issue were my write-ups of laboratory experiments. In the first case, a teacher asserted that if my experimental results didn't fit accepted theory, it was my duty as an engineer to make them fit. The second rebuke concerned my plots of measured triode valve characteristics. Apparently I took the instrument manufacturers' stated error bounds too seriously: the tolerance spreads that I had estimated for my voltage-current characteristics were deemed too broad and hence (statistically) unreasonable.

These "practical observations" surely disoriented me. Later, designing and constructing stable, broadband tunnel-diode (negative resistance) amplifiers as per my Ph.D. requirements proved troublesome: my waveguide designs largely ignored possible machining and fabrication tolerances, and uncertainties due to mounting effects and mechanical pressure for the devices under test. I also ignored model uncertainties, particularly in the fragile tunnel diodes. I then spent months experimentally wrestling stable amplification from my experimental amplifiers.

It didn't occur to me to try to explain what the display on my even then ancient spectrum analyzer confronted me with—in retrospect, chaos. Had I changed the course of my research towards a theory that predicted what I observed, who knows what discoveries I might have made? Someone else invented chaos theory.

I rubbed shoulders with circuit theory "synthesis" purists and "nuts-and-bolts" engineers, most of whom objected to the use of digital computers for solutions to electrical engineering design problems—other than in narrowly interpreted analysis studies (solution validation). In the 1960s and 1970s, academics and others in positions of influence deemed computer-aided design and optimization as "not engineering," to be taken seriously only because these activities would hurt engineering students. Engineers who scribbled on the backs of envelopes thereby demonstrated their "feel" for a problem (and hence their expertise) while those who preferred "closed-form" solutions demonstrated their agility in the realm of mathematics.

While I became attracted in my undergraduate years to methodologies for design that accounted for manufacturing tolerances and statistical uncertainties, I did not initiate research in this area until 1970. I introduced post-production tuning into the so-called "design centering" and tolerance assignment problem [1] and went on to advance yield-driven design and design with tolerances. A key paper (Bandler, Liu and Tromp [2]) further embodies uncertainties in component modeling, in manufacturing and in so-called parasitic effects. All this started more than fifteen years before implementation of these features in commercial microwave CAD software. The microwave community at large saw no need for this technology, until championed by Robert Pucel of Raytheon in the 1980s. My paper with Steve Chen [3] encapsulates the state of the art.

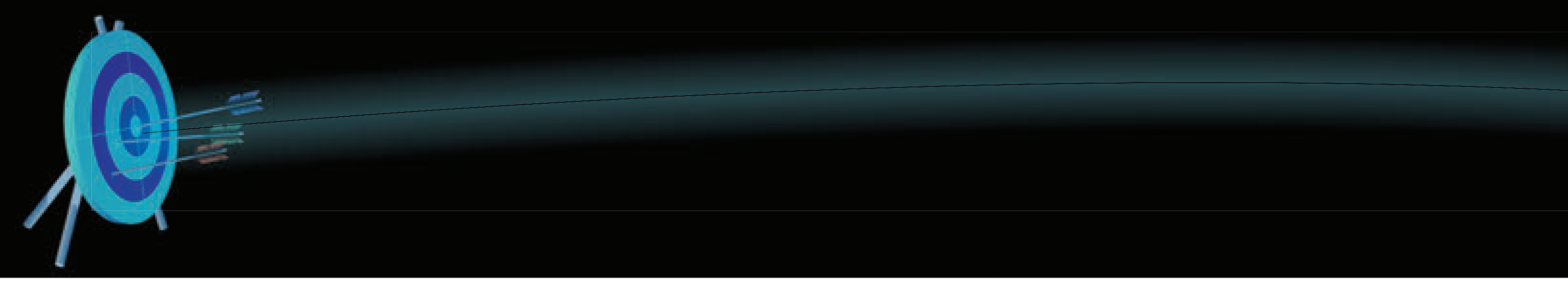
In the late 1970s I formed collaborations with Radek Biernacki (now with Agilent Technologies) and mathematician Kaj Madsen of the Technical University of Denmark. Radek joined me for two years as a postdoctoral fellow and introduced me to analog fault diagnosis, and Kaj, who spent a sabbatical summer with me, led me to his robust nonlinear optimization algorithms.

The Debut of OSA

I formed my company Optimization Systems Associates (OSA) in 1983. OSA's first major assignment was to reengineer the inhouse simulation and optimization software for the flagship product line of the aerospace technology company ComDev (Cambridge, Ontario): microwave multiplexer (waveguide) hardware for communication satellite applications [4], [5].

EEsof Inc. of Westlake Village, California, commissioned me in the mid 1980s to develop new optimization tools for their recently released circuit simulation tool Touchstone.

Meanwhile, in 1985, Robert Pucel of Raytheon Research Division in Lexington, Massachusetts, asked me to do a feasibility study for yield-driven circuit design. Following its success, he invited OSA to contribute to Raytheon's initiative towards the Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) Program. This brought OSA together with



software vendor Compact Software of Patterson, New Jersey. Encouraged by Bob Pucel, one of Compact's immediate aims was to avail itself of a yield-driven design capability.

I asked Radek Biernacki to rejoin my group. With Q.J. Zhang, Steve Chen, Monique Renault, and others, we reengineered the immense SuperCompact Fortran code and contributed to Compact Software's Microwave Harmonica (for harmonic balance simulation). OSA introduced yield-driven design, engines for (statistical) simulation and optimization, and entirely new documentation to Compact Software's premier products.

Our involvement with Compact Software and Raytheon ended in 1989.

OSA Goes Solo

OSA initiated its own commercial optimization-oriented software products in 1988 [6].

Meanwhile, Ansoft Corporation, Hewlett-Packard, Sonnet Software and others offered simulators that solved Maxwell's equations to validate complex microwave structures.

I had frequently spoken of driving electromagnetic solvers in an optimization loop. So I asked both Ansoft Corporation and Hewlett-Packard to send OSA their simulators, without charge because OSA was a shoe-string company and because I believed we offered value to them. Ansoft was unresponsive; Hewlett-Packard representatives openly ridiculed me: surely I knew that their "full-wave" electromagnetic simulator might take, if not hours, perhaps days or weeks on a useful structure to complete a frequency sweep for just a single set of design parameters?

After Jim Rautio, founder and president of Sonnet Software, freely availed us of his flagship electromagnetic simulator "***em***," OSA benchmarked 1992 with "Empipe." Empipe [6] could incorporate, on-the-fly, simulations by Sonnet's ***em*** into OSA's user-friendly optimization system OSA90, providing RF and microwave designers for the first time not only electromagnetics-based optimization but also yield-driven electromagnetic optimization for structures with arbitrary geometries, albeit for modest sized problems.

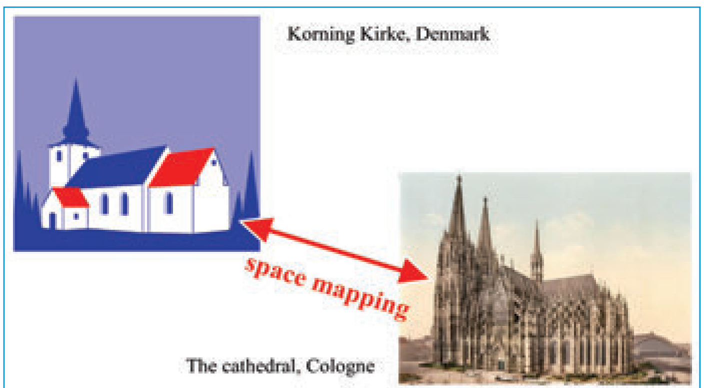


Fig. 1. In the summer of 1993, in the outskirts of Copenhagen, space mapping is conceived as an association of models. [Cologne Cathedral from The Photochrom Print Collection, Library of Congress; Korning Kirke courtesy Asbjorn Lonvig.]

It still took weeks before Hewlett-Packard agreed to send us their electromagnetic simulator "HFSS" (high frequency structure simulator) free of charge. And once Ansoft got wind of our success with HFSS, they promptly sent us their own "Maxwell Eminence" simulator.

The era abounded with challenges and surprises [7]. In Dan Swanson's words, "[OSA90 is] the first commercially successful optimization scheme which included a field-solver inside the optimization loop" [8].

Then, on November 20, 1997, after mutual visits and demonstrations in Dundas, Ontario, in Santa Rosa, California, and elsewhere, Hewlett-Packard acquired OSA. Weeks later, Steve Chen and Radek Biernacki, OSA's principal contributors of the time, relocated to Santa Rosa.

The Birth of "Space Mapping"

In 1993 Salvador Talisa of Westinghouse Corporation challenged us with the design of a certain high-temperature superconducting (HTS) filter [9]. I asked graduate student Peter Grobelny to see what OSA's Empipe could achieve with Sonnet's ***em***.

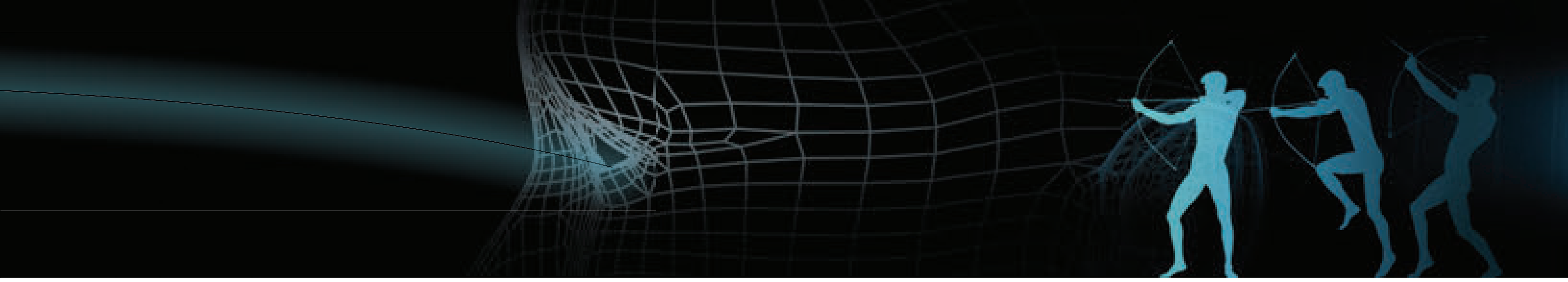
Bad news. It took some two weeks of CPU time on our Sun SPARCstation 1 for a full evaluation of just the starting point (the initial design) along with the six perturbed points (sets of parameter values) for approximating the first-order derivatives with respect to the filter's six design variables. I estimated up to two years of CPU time for a formal optimization using the conventional approaches embodied in OSA's software—a result dramatically at odds with what a skilled engineer might have achieved via an experience-tested "feel" for the problem.

That summer (1993), I spent a week in discussions with Kaj Madsen, both in Denmark and at a conference in Sweden. I recall my obsession—and, not surprisingly, his startled skepticism—while we strolled in a forest with the notion of "model," the recognition of "real" objects (churches, houses) on the horizon and "mapping" them to an element of a possible "library" of preconceived images (models) in one's brain. More specifically, extracting certain essential features of the objects that allowed them to be recognized (by virtually anyone), named, and manipulated in an as yet indefinable way. A question was, how could one associate these "fuzzy" features with a related "model" so as to drive a design optimization of the object without expending too much computational effort on the object itself. The process seemed at once obvious and hidden; iteration was surely required, as well as scaling, shifting, rotating, twisting, and elimination of detail. See Fig. 1.

I was searching not for mathematics but for the engineer's "feel."

On my return flight from Frankfurt to Toronto I jotted down my ideas. Back in Canada, I handed my notes to my collaborator Steve Chen to see if he could make sense of what I had written. Two weeks or so later, after I had all but forgotten about my scribbling, Steve asked me to look at his computer monitor. I saw an equal-ripple response. Nothing unusual: equal-ripple responses from optimized filters were customary. The astounding difference here, he pointed out, was that he had produced this response not by a fast equivalent circuit model within our own OSA90, but by Sonnet Software's ***em***—in just three simulations, driven by OSA90. My notes, Steve Chen said, were correct, apart from some redundancies in notation.

Space mapping was born.



In effect, by cleverly exploiting an underlying surrogate, the electromagnetic simulator was taken out of the classical optimization loop: the engineer's mysterious "feel" was emerging.

Radek Biernacki should be credited with coining the expression "space mapping." (Memory has a habit of playing tricks, so I checked this recently with him.)

In the following sections, I attempt to explain and illustrate the many faces of space mapping.

The Essence of Space Mapping

The sketch in the sidebar to the right roughly follows our so-called "aggressive space mapping" (ASM) approach, published in 1995—particularly when fine model data is frugally exploited [10]. The key to ASM was our utilization of Broyden's famous "rank-one update" for estimating the Jacobian involved in the numerical solution of the relevant nonlinear equations [11]. It was Kaj Madsen who first realized a space mapping iteration update as a classical quasi-Newton process.

Most researchers who subsequently confirmed our space mapping methodology (and published their results) exploited the "aggressive" approach—ASM.

Why didn't mathematicians advance this generic formulation? Simple. They stayed away from the messy engineering side of the modeling coin. So long as only localized information is exploited by their algorithms—function values, first-order derivatives, and possibly second-order derivatives—only a "conventional" attack is feasible. Put another way, the "**parameterized model**" that drives the conventional mathematical optimization process is limited by its generic assumptions (linear, quadratic, i.e., local modeling of functions). For engineering design, space mapping is underpinned by a "quasi-global" formulation: a well-conceived, parameterized model based on engineering knowledge, that represents—hence, is "physics-based"—expensive "fine" model behavior relatively well. An appropriate algorithm can then yield excellent designs after only a handful of fine model evaluations. Under certain circumstances, between two and four such simulations may suffice, unlike the tens, hundreds or even thousands required by conventional optimization, even if exact gradients (first-order sensitivities) are available.

Then why didn't the design experts explicitly formulate space mapping in a manner widely understandable? They often used it and continue to do so. (In fact, at about the same time as we published our work, Tony Pavio of Texas Instruments did utilize a bona fide space mapping process to solve filter design problems [12], [13]). Simple, also. Engineers stayed away from the increasingly sophisticated nature of the (by then canned) solution techniques. For example, the basis of aggressive space mapping is the formal solution of nonlinear equations [10].

I offer here a simplistic explanation. To formulate the space mapping concept, you need a comfortable foot in the domains of both engineering and mathematics; not one simulator (model), but **two** simulators (models) are concurrently harnessed, ones that must be coupled and interact intelligently on-the-fly off each other. One simulator, the nonlinear, physics-based, quasi-global "coarse" model drives the also nonlinear, high-fidelity physics-based "fine" model.

A Space Mapping Methodology

Preliminaries

Study a discipline/conduct experiments/become an expert.

Develop a library or resource of fast, parameterized coarse models (surrogates) and inexpensive ways of invoking them.

The Specific Problem

Focus on the device under test/the real-life situation/the fine model/the expensive-to-compute system (there are many labels: validation, high fidelity, …).

Select a representative (reference) coarse model, preferably capable of meeting your design specifications ("implicit space mapping" exploiting preassigned parameters and "output space mapping" that corrects or shifts responses can aid in this process).

The First Iteration

Optimize your fast coarse model until your specifications are optimally exceeded (if possible).

Assign the resulting parameter values to the fine model.

Expedite (simulate, run) the fine model.

If the specifications are met (implying that your coarse and fine models are sufficiently aligned), **STOP**.

Subsequent Iterations

BEGIN: to better match the observed behavior of the fine model use available fine model data (generate more, if necessary, but frugally) to augment/update your coarse model with a mapping. We call this step **parameter extraction** (a surrogate update, a training process).

Optimize your mapped (space-mapping-augmented) coarse model until your specifications are optimally exceeded (by this step they preferably should be).

Assign the resulting parameter values to the fine model.

Expedite (simulate, run) the fine model.

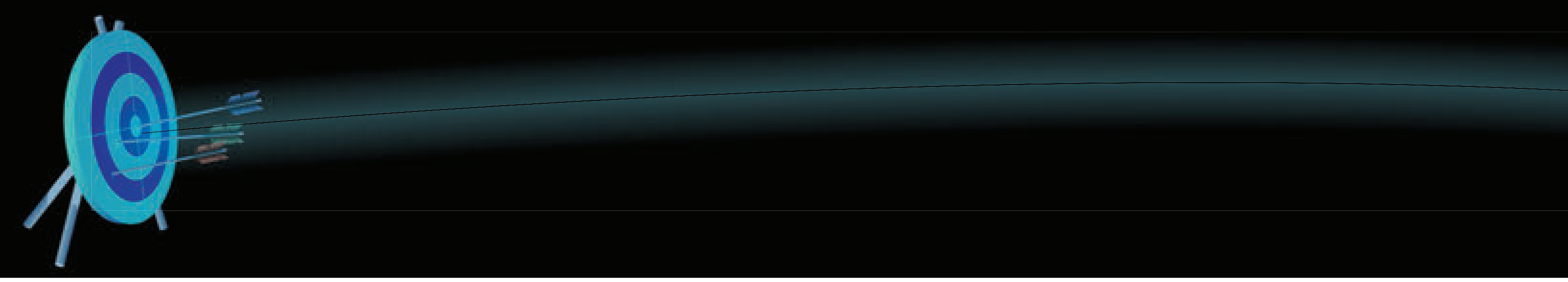
If the specifications are met (implying that your coarse and fine models are sufficiently aligned), **STOP**.

If a specified number of iterations (or other stopping criteria) are reached, **STOP**.

Go to **BEGIN**.

The process can fail ("intuition" often fails); remedies are discussed in the literature. You may consider "implicit space mapping" (see a later section) to improve the coarse model.

A comment (for advanced readers). In the original or "input" space mapping methodology, an explicit re-optimization of the mapped coarse model is averted by assuming that the initial coarse model optimally satisfies the design specifications, and that any manipulation or mapping of the input parameters would not improve the situation. In this case, the aim of the space mapping optimization process is to predict a set of fine model design parameters such that the fine model response matches the already satisfactory (target) coarse model response.



In the field of engineering, parameterized, physics-based coarse models abound, covering every conceivable variation from super-fast analytical or empirical to slower, coarse-mesh numerical.

When an engineer explains a clever design methodology based on tradition or experience, it often seems impossible to escape from the jargon of the specialty in question. But that mental flexibility is exactly what is needed to explain the space mapping concept and make it accessible. In fact, hand-waving can illustrate the concept—no "expertise" needed. Following the public unveiling of the space mapping concept in 1994, it has often reappeared in different guises.

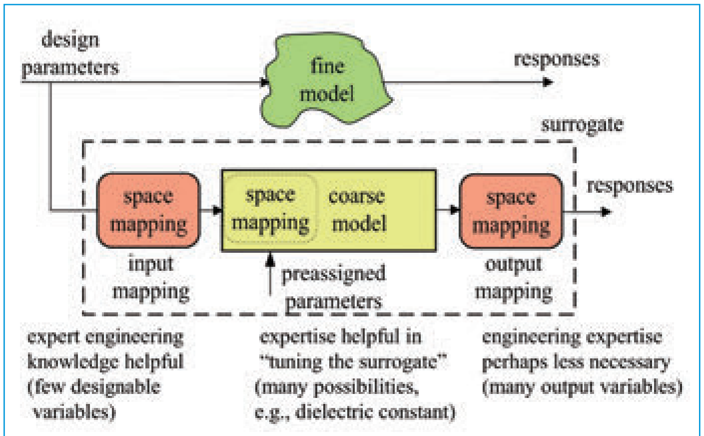


Fig. 2. The evolution of the space mapping concept from 1994 to 2004.

The Original Input Space Mapping

In our 1994 paper [14], we first proposed space mapping as a simple way to mate the efficiency of circuit optimization with the accuracy of electromagnetic solvers. The approach was conservative, the forerunner of later work in enhancing model libraries: several fine model simulations were necessary for developing a serviceable mapping upfront. The aggressive space mapping methodology [10] followed later.

Input space mapping can be expressed as

$$\boldsymbol{x}_c = \boldsymbol{P}(\boldsymbol{x}_f)$$

where $\boldsymbol{x}_c$ and $\boldsymbol{x}_f$ are vectors that represent, respectively, the coarse and fine model (input) design parameters. The mapping is expected to be near-linear in the case of well-matched models.

As a traditional first step, conventional optimization is carried out using the coarse model. The resulting solution is denoted $\boldsymbol{x}_c^*$.

Once a mapping is established, an inverse determines the fine model solution as the image of $\boldsymbol{x}_c^*$, namely,

$$\boldsymbol{P}^{-1}(\boldsymbol{x}_c^*)$$

The required parameter extraction step in effect calibrates the coarse model against the fine model to minimize differences and off-sets between them, and permits an update of the mapping. In general, to make the overall process desirable, the coarse model should be significantly faster (a hundred or more times) and much cheaper to execute than the fine model.

Space Mapping: The Experts' First Impressions

Vittorio Rizzoli is world-renowned in nonlinear systems and microwave electromagnetics. When I faced him across his huge desk in his office in Villa Griffone (University of Bologna, Italy), the space mapping concept had not yet been announced. I asked him to listen for a moment while I sketched my idea with a few words accompanied by some hand waving. Then I waited. For a moment his stare was blank. Seconds later a look of amazement swept across his face, a look that said, "Of course!" I'm not sure whether he pounded his desk.

In 1994, in a hall of the San Diego Convention Center that overlooked the harbor, former EEsof cofounder Bill Childs was one of many who had gathered around me in my "open-forum" (poster) presentation—my first publication of space mapping. He waited until the crowd had thinned before protesting that I was concealing the key to my algorithm. Pointing at the simple formula that mapped $\boldsymbol{x}_f$ to $\boldsymbol{x}_c$ I assured him that I had divulged absolutely everything. Unconvinced, he threatened to bring his concerns to the attention of the conference's technical program committee.

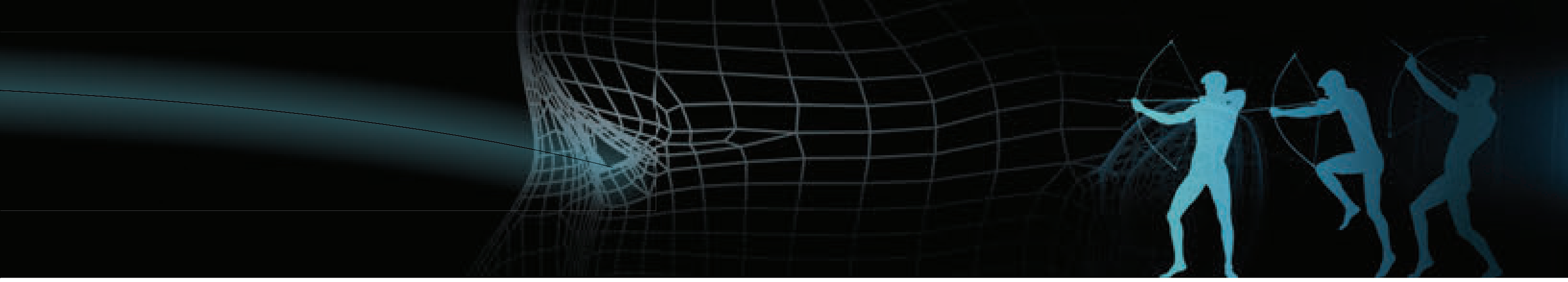
(Ironically, I had toyed with the idea of keeping space mapping secret; exploiting the process in OSA's software to possible huge advantage: other vendors might have taken years to catch up.)

After the session, I found Ralph Levy—a respected consultant in the microwave filter business—relaxing in an armchair. Knowing that he hadn't visited my poster presentation, I sketched the space mapping concept by hand-waving, as I had done with Vittorio. His eyes lit up almost immediately. "I get it!" he said and instantly recalled designing a filter in which he aligned (calibrated) his circuit response against that of an electromagnetic simulation at a certain frequency point and found that his updated filter model then readily facilitated a good solution.

A noteworthy item in the history of OSA is OSA's failure in 1995 to win a contract under the MAFET (Microwave and Analog Front-End Technology) Program from DARPA (the US Defense Advanced Research Projects Agency). The title of our ambitious proposal was "Space mapping techniques for intelligent, automated, direct optimization-driven electromagnetic design of microwave and millimeter-wave circuits."

The OSA90/hope user's manual was updated to include a very early space mapping option [15].

Rice University professor and mathematician John Dennis and I first met in 2000 in Lyngby, Denmark, at the First International Workshop on Surrogate Modelling and Space Mapping, co-organized by Kaj Madsen and myself [16]. He and his team had already explored algorithms for the management of surrogates for optimal design. The space mapping concept proved new to them. Following the workshop, he wrote, "The idea of a space map is very appealing. I had not heard of it before, but it seems to have proved its worth in electrical



engineering. John Bandler, an electrical engineer and entrepreneur from McMaster University in Ontario, seems to have originated the idea, and he has a stable of graduate students applying it in several variations" [17].

The Evolution of Space Mapping

An early industrial enthusiast of space mapping was Jan Snel of Philips Semiconductors, who engaged me in 1998 to instruct him and his colleagues in the art. In turn, Jan inspired academic research in The Netherlands in this area [18], [19], [20], [21].

The space mapping approach has evolved over the past twenty years into a space mapping technology. The half-way point is demarcated by a review of the state of the art [22] and a paper that reviews implicit and output space mapping [23]. These papers are co-authored with some of my important collaborators of the time; they already introduce illustrative examples of an everyday nature—the so-called "cheese-cutting" and "wedge-cutting" problems. These examples, which I conceived while attending an opera in Copenhagen for a seminar to Kaj Madsen's students the next day, are launching pads for explanations that anyone should be able to grasp.

The space mapping concept can be layered with, augmented by, and reinvented in conjunction with other modeling schemes, parametric or otherwise, including artificial neural networks—neuro-space mapping [24]. The drive to automate and make the processes more robust continues (my colleague Slawek Koziel, now with Reykjavik University, Iceland) [25], [26], [27].

Space mapping optimization belongs to the arena of surrogate-driven optimization methods [28], [29]. Space mapping is distinguished by the effective utilization of enhanced (mapped) quasi-global coarse models that harness the essential features of the fine model in the domain of interest. Vicente offers an overview [30].

By 2003, my group offered several variations of space mapping, e.g., input (the original form), implicit (using preassigned parameters), output (employing direct manipulation of responses, etc.). See Fig. 2 on page opposite. Each form enjoys advantages and disadvantages, and can be used in concert.

In the input (original) space mapping process, a typical problem has relatively few designable (optimizable) variables. Here, expert engineering knowledge is helpful. Implicit space mapping exploits preassigned parameters—those many possible parameters of a real structure that are usually predetermined and fixed ahead of formal optimization. In the coarse model, however, they are free to be used to improve the alignment between the coarse and fine models. Many possible preassigned parameters suggest themselves; popular in electromagnetics-based design is the dielectric constant, which can be decomposed and directed to aid in independently "tuning" various sections of a structure. Thus, expertise for "tuning the surrogate" is helpful. Engineering expertise is perhaps least necessary in executing output space mapping, since the technique consists of shifting or manipulating the coarse model responses directly at the response level. Many output variables are usually involved, and a robust mathematical platform is desirable.

The invasive (expertise required) tuning space mapping process exploits tuning ports and simulator-based models [31]. The surrogate is a tuning model based directly on the fine model.

Space mapping and its spin-offs continue to flourish in various engineering practices, for example, neural-based space mapping for large-signal statistical modeling of nonlinear devices [32], [33]. Recent technical reviews can be found in *IEEE Microwave Magazine* [34], [35], [36].

The essential difference—oversimplified here for the sake of discussion—is that space mapping arises out of an understanding of the "feel"

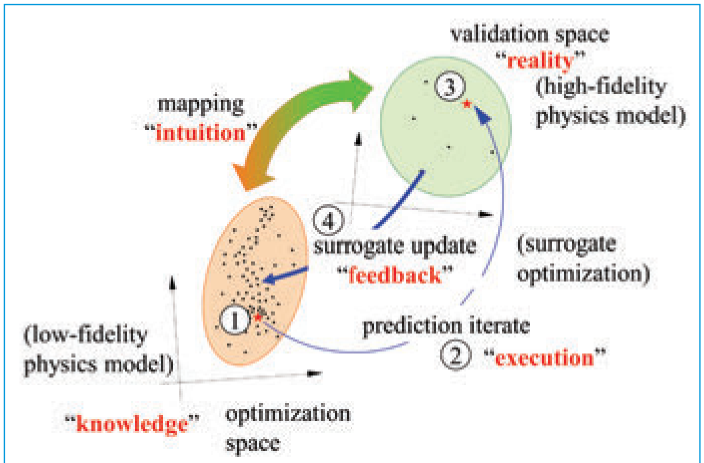


Fig. 3. The space mapping concept as it has evolved over the years (Bandler *et al.* 1994-)

that an experienced engineer has for a complex engineering design problem, while the generic surrogate-based approach arises from the "feel" that a mathematician has for a generic optimization problem. Confusion sets in when words like surrogate, model, and simulation are tossed around arbitrarily and interchangeably to mean almost any representation of anything. One thing is for sure: surrogates, models, and simulations imply underlying knowledge, nowadays typically the physics embodied in a simulator. How this knowledge is **cognitively manipulated**—from the "inside" or from the "outside"—depends on whether the designer is oriented towards engineering or mathematics (or perhaps both).

A Semi-Technical (Advanced) Explanation

My current thinking about the space mapping concept is depicted by Fig. 3. The validation space ("reality") represents the fine model, for example, an expensive-to-compute, high-fidelity physics model. The optimization space, the only arena in which iterative, conventional optimization is carried out (indicated by the multitude of points), incorporates the coarse (or surrogate) model, for example, the low-fidelity physics or "knowledge" model. There is a prediction or "execution" step, where the results of the mapped coarse or surrogate model are assigned to the fine model for validation. Then, if the specifications are not satisfied, relevant simulation data is transferred back to the optimization space ("feedback"), where the mapping-augmented coarse model or surrogate is updated (enhanced) following an iterative optimization process we term "parameter extraction." The mapping element itself embodies the "intuition," certainly essential to the so-called "feel" for the problem. It "distorts" the coarse model to align it with the fine model.

Cognitive Analogies

In 2002, while waiting at the Copenhagen airport for a flight to Frankfurt after visiting Kaj Madsen, I picked up a copy of *The International Herald Tribune* for February 21, 2002 [37]. On page 7 I found an article by Sandra Blakeslee reprinted from *The New York Times* entitled "The brain's automatic pilot."

Having just addressed Kaj Madsen's students on everyday interpretations of the space mapping methodology (e.g., the aforementioned "cheese-cutting" problem), I was struck by the analogy. Blakeslee wrote, "[certain brain] circuits are used by the human brain to assess social rewards …" and that "… findings [by neuroscientists] … challenge the notion that people always make conscious choices about what they want and how to obtain it." Notice that notions of intuition, unconscious choice, or "feel" manifest themselves here.

Blakeslee quoted Gregory Berns (Emory University School of Medicine): "… most decisions are made subconsciously with many gradations of awareness." She also quoted P. Read Montague (Baylor College of Medicine): "… how did evolution create a brain that could make … distinctions … [about] … what it must pay conscious attention to?" The implication that (Darwinian?) evolution has **optimized** what humans need to pay attention to and how to respond is intriguing. For example, a child is prone to ensure that his or her slice of birthday cake is no smaller than anyone else's.

Blakeslee continued with "… the brain has evolved to shape itself, starting in infancy, according to what it encounters in the external world" and that "… much of the world is predictable: buildings usually stay in one place, gravity makes objects fall …" The ideas of experience, expertise, or some sort of "feel" manifest themselves here. And there is no mention of any **conscious** technical expertise in the sense of any mastery of the mathematical formulas or dynamical equations that might model these processes.

I add my own nomenclature and interpretation in bold and square brackets, as follows, to expose the analogies with my technical perspective of space mapping. Blakeslee wrote, "As children grow, their brains build internal models [**coarse models, surrogates**] of everything they encounter, gradually learning to identify objects …" Not a few things, but **everything**. Further, "… as new information flows into it [**fine model data**] … the brain automatically compares it [**parameter extraction**] with what it already knows." "… if there is a surprise … the mismatch [**response deviation**] … instantly shifts the brain into a new state [**surrogate update, switch coarse model, start on a new model, …**]." Finally, "Drawing on past experience [**knowledge + intuition**] … a decision [**prediction, execution**] is made …"

The foregoing appears entirely intuitive, based on experience, and the memory and processing power of the brain, whether human or animal—animals walk, hunt, fly, etc., obviously without consciously formulating any dynamical equations.

On page 7 of a recent book [38], Eagleman writes, "The brain runs its show incognito." For example, "In 1862, the Scottish mathematician James Clark Maxwell developed a set of fundamental equations that unified electricity and magnetism. On his deathbed, he coughed up a strange sort of confession, declaring that 'something within him' discovered the famous equation, not he." On page 17 Eagleman writes, "… the mind" [according to Freud] … "was rather like an iceberg, the majority of its mass hidden from sight."

On page 33, "Helmholtz (1821-1894) had begun to entertain the suspicion that the trickle of data moving from the eyes to the brain is really too small to account for the rich experience of vision. He concluded that the brain must make assumptions about the incoming data, and that these assumptions are based on our previous experience."

Previous experience implies an arsenal of physics-based "coarse" models, candidates of which are updated "on-the-fly" by incoming data, and harnessed in a decision-making process. Then "… the brain uses its best guess …"

Eagleman deepens his observations on page 48. He suggests that "We're able to catch baseballs only because we have **deeply wired internal models of physics** [bold is my emphasis]." That "These internal models generate expectations about when and where the ball will land given the effects of gravitational acceleration." He explains that "That the visual cortex is fundamentally a machine whose job is to generate a model of the world." On page 49, he continues with "This unpredicted information adjusts the internal model so there will be less of a mismatch in the future."

Again we see the idea of the development of suitable coarse models and their enhancement, for example, through a parameter extraction process followed by a space mapping update.

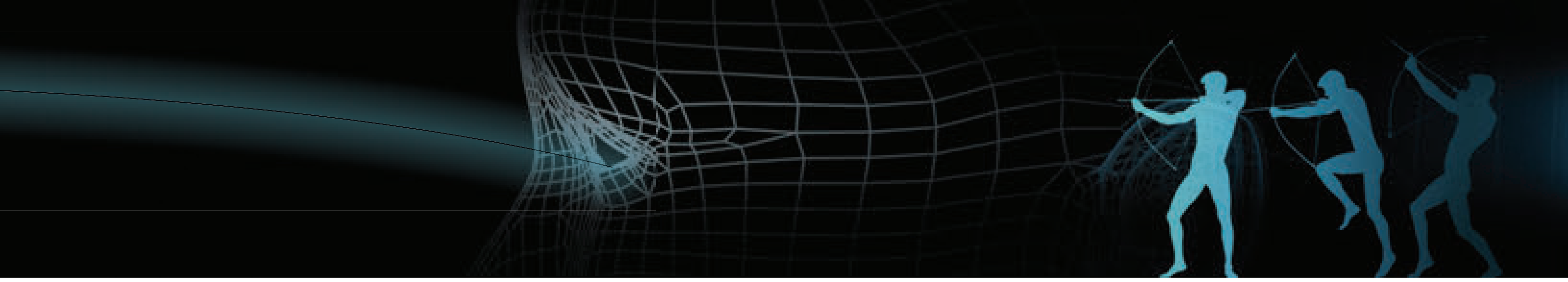
The Grand Design

Hawking and Mlodinow [39] (p. 45-46) write that, "it is pointless to ask whether a model is real, only whether it agrees with observation." "The brain, in other words, builds a mental picture or model." (p. 47). On page 172, they declare that "Our brains interpret the input from our sensory organs by making a model of the outside world … trees … people … other universes …"

How good need a model be? The authors' criteria on this are found on page 51. They write, "A model is a good model if it:

1. Is elegant
2. Contains few arbitrary or adjustable elements
3. Agrees with and explains all existing observations
4. Makes detailed prediction about future observations that can disprove or falsify the model if they are not borne out."

This suggests the notion that the modeling process itself—in the present case the manipulation of a mapped (mapping-augmented) quasi-global coarse model—is a model.



Selecting a Pair of Shoes

After a brief brush with "the grand design" of the universe we turn to the most down-to-earth of activities, that of selecting a pair of shoes that fit. See Fig. 4. This example illustrates everyday common sense formalized as a space mapping process.

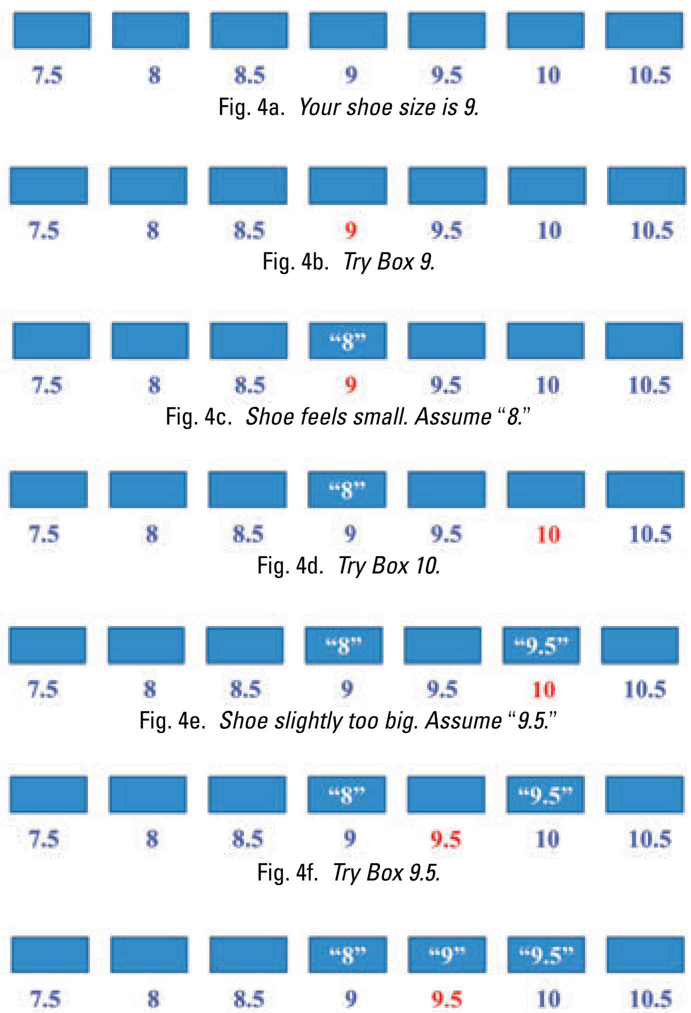


Fig. 4a. *Your shoe size is 9.*

Fig. 4b. *Try Box 9.*

Fig. 4c. *Shoe feels small. Assume "8."*

Fig. 4d. *Try Box 10.*

Fig. 4e. *Shoe slightly too big. Assume "9.5."*

Fig. 4f. *Try Box 9.5.*

Fig. 4g. *Shoe fits!*

Fig. 4. A "shoe-selection" problem.

You are shopping for shoes in a shop you are unfamiliar with. The shoeboxes of interest are identified by numbers (presumably) representing the sizes of their contents: Box 7.5, Box 8, Box 8.5, etc. Assume for simplicity there is only one available width: normal. Prior knowledge: let your shoe size be "9" and your width normal. Your first attempt would surely be a look into Box 9. You try on a shoe from Box 9; it feels small; perhaps it's an "8," a whole size too small. You would likely next select Box 10. You try on a shoe; it feels too roomy; perhaps it's a "9.5," half a size too large. Your next, and hopefully final, choice would surely be Box 9.5. If shoes from this box don't quite fit, you would likely give up this particular line of shoes.

Note that you tried three likely sizes so far; not too frustrating. You made certain assumptions about the labeling of the available selection. The available shoes seemed smaller than your expectations and were not too uniformly graded—if your judgment can be trusted.

We could add shoe widths, for example, and expand this illustration to two dimensions.

Some Applications

A distinguished team at ComDev [40] optimized a 10-channel output multiplexer involving 140 optimization variables. See Fig. 5 on the following page for the optimal responses of the multiplexer, comparing ideal (circuit theory) responses, responses calculated by the electromagnetic simulator HFSS, and subsequent measured responses. Aggressive space mapping was used.

Another illustration is the optimization of a microwave hairpin filter using implicit space mapping and the simulator ***em*** from Sonnet Software as fine model [34].

Redhe and Nilsson [41] applied space mapping to a structural optimization problem involving a finite element vehicle model requiring computing times of the order of 100 hours. For a Saab 9-3 driven straight into a steel barrier at 56 km/h, they report that space mapping cut calculation times by three fourths compared with traditional response surface optimization methods; and penetration of the passenger space was reduced by 32 percent without compromising other crashworthiness parameters.

Further illustrations—too numerous to list here—encompass electromagnetics-based microwave circuit design, active device modeling, device modeling techniques that combine space mapping with artificial neural networks [42]; antenna design; design optimization problems in the fields of electronics, photonics, and magnetic systems [43],[44],[45],[46]; and applications in chemical, civil, mechanical, aerodynamic, aeronautical and aerospace engineering systems.

Ben-Ayed *et al.* [45] and Berbecea *et al.* [46] used output space mapping to address the optimal design of electromagnetic devices. Banda and Herty applied space mapping to the dynamic compressor optimization of gas networks [47]. Lass *et al.* wanted to solve optimal control problems for real-world applications [48]. Marheineke and Pinnau [49] performed a feasibility study for transport processes coming from the fields of fluid dynamics, semiconductors and radiation. Vivier *et al.* exploited output space mapping [50]. Prieß and Slawig [51] applied aggressive space mapping to the optimization of a one-dimensional marine ecosystem model.

Marheineke *et al.* [52] studied space mapping within fluid dynamics. "To control random particle dynamics in a turbulent flow," the authors write, "we suggest a Monte-Carlo aggressive space mapping algorithm which yields very convincing numerical results." They say, "we show that space mapping is a very elegant method for our dispersion problem in terms of range of applicability, power and efficiency." "To the authors' knowledge this is the first numerical treatment of a stochastic control problem by space mapping."

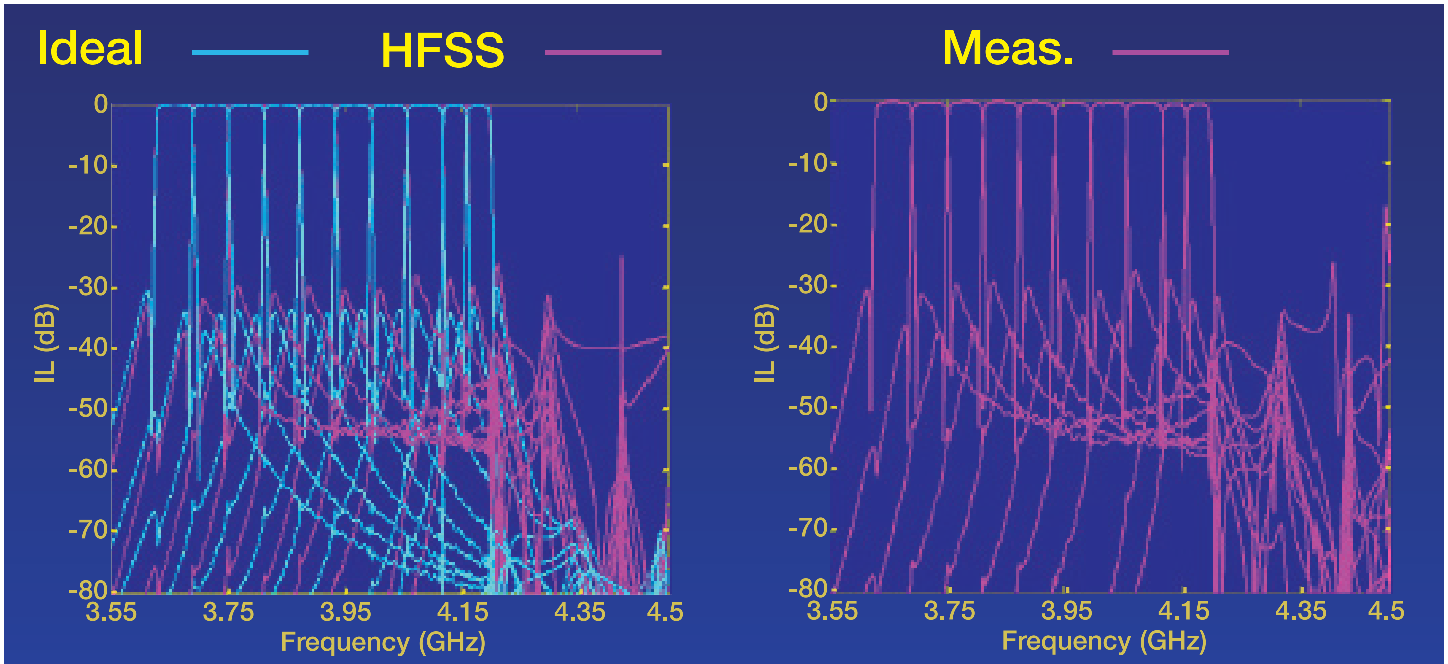


Fig. 5. Aggressive space mapping design optimization of dielectric resonator multiplexers by Ismail *et al.* [40]: a 10-channel output multiplexer, 140 variables.

Less is Always More

In 1967, a senior academic declared that my proposed research into computer-aided design (CAD) had already been fully explored. In 1974, experts predicted that my work in CAD with tolerances would never prove useful; in 1985, Raytheon Research Division hired me to work on CAD with tolerances; in 2004, I received the IEEE Microwave Theory and Techniques Society's Application Award for my work on CAD with tolerances. In 1993, I told Hewlett-Packard representatives that I wanted to link their "HFSS" system to my "OSA" optimization software; they ridiculed me; in 1997, Hewlett-Packard bought my company.

It took me an honors degree in electrical engineering that included feedback control, followed by 30 years of research into optimization techniques and engineering design technology, to stumble across space mapping. Space mapping offers two mathematically-based utilities: (1) optimization "on-the-fly," and (2) "off-line" model enhancement for later use. The key to space mapping optimization "on-the-fly" is to intelligently exploit the information flow between two available simulation levels. The key to "off-line" modeling is to use the fine model to train—to (re)calibrate—a suitably mapped coarse model over a domain of interest.

For topics triggered by this article see, for example, Ramachandran [53] on the notion of mirror neurons, and adaptive control involving a reference model [54].

Psychologist and Nobel laureate Daniel Kahneman [55] describes a System 1 way of thinking that is fast and intuitive and a System 2 that is slow and effortful. "Expert intuition strikes us as magical," he writes, "but it is not. Indeed each of us performs feats of intuitive expertise many times each day." Like selecting a pair of shoes that fit? But Kahneman doesn't separate the concept of a trained fast model (expertise, knowledge) from an "on-the-fly" updating process (space mapping).

In "The essence of space mapping: less is more," my long-time colleague Qingsha Cheng and I listed certain properties of space mapping [56]: "build a thin layer around existing knowledge, minimally complex (usually linear or very simple); for model enhancement, the data required is small (Helmholtz's trickle?); the iteration count is small; manual implementation is often possible; the resulting enhanced model or design can be astonishingly good."

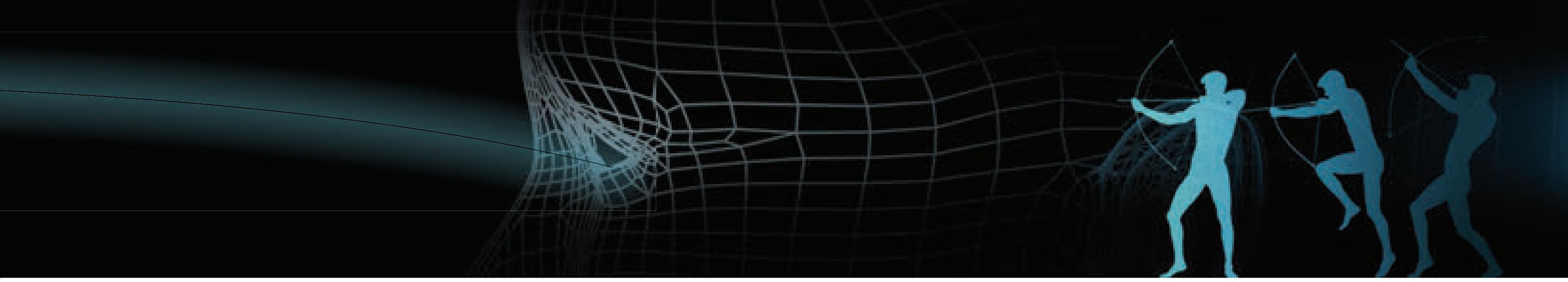
It seems to me that if knowledge can be built into a predictive model, so can "feel" and intuition.

If at First You Don't Succeed

So why does space mapping work? It works, I have often said, because it is a natural mechanism for the brain to relate objects or images with other objects, images, reality, or experience; because "experienced" engineering designers (experts), knowingly or not, routinely employ it to achieve complex designs; because, with virtually no mathematics, simple everyday examples confirm it. This has been amply illustrated over many years with everyday examples that conform to today's understanding of how the human brain itself treats models of "reality."

According to the legend of Robert the Bruce, "If at first you don't succeed, try, try again." But how many times are you willing to try? If you're familiar with a certain process—say, knotting your tie so that it hangs properly—and you don't realize success in one or two tries, you may feel frustrated. If you are an expert, shouldn't you get it right in three tries or less? If it is essential that you learn a new skill, you will usually be willing to keep trying (learning process). Yet, if you require an unexpectedly large number of tries, you may have to overcome your heightening frustration. This is common sense.

Aggressive space mapping efficiently invokes inner loops of conventional optimization—common sense at work—often yielding excellent



results in an acceptable two or three iterations. The aggressive space mapping update/execution process is itself optimization on a higher level—meta-optimization?—a process that uncannily mimics both common sense and the expert's "feel." It surely mirrors an optimal strategy for human survival, honed by evolution, for rapid learning and decision-making under extreme duress.

It is ironic that the very same generic process is as easy to explain to your next-door neighbor as it has proved difficult for an expert to explain to a fellow expert in the next cubicle.

Space mapping facilitates multidisciplinary engineering design and modeling; it offers a quantitative explanation for the engineer's "feel"; it offers everyone "more" for "less"; and by the definitions of Hawking and Mlodinow [39] it may even qualify as "elegant."

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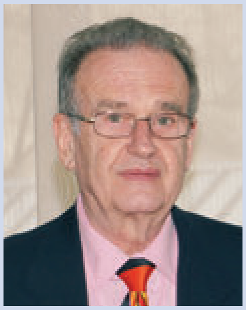

John Bandler (LFIEEE) is professor emeritus at McMaster University and president of Bandler Corporation. A previous company he founded, Optimization Systems Associates, was acquired by Hewlett-Packard in 1997. John studied at Imperial College of Science and Technology and received his degrees from the University of London.

Based on John's work, advances such as design with tolerances, yield-driven design, and electromagnetic optimization—once academic fantasies—are now taken for granted by microwave engineers. His implementations into major commercial design tools have impacted high-frequency and microwave design initiatives world-wide. John introduced space mapping in 1994. From automotive crashworthiness to magnetic systems, his concept has been adopted into design portfolios across the entire spectrum of engineering, making possible the high-fidelity design of devices and systems at a cost of only a few high-fidelity simulations. John has published more than 480 technical papers, served on editorial and review committees, and been guest editor of several special issues.

John is a Fellow of several societies including the Canadian Academy of Engineering and the Royal Society of Canada. In 2004, the IEEE MTT Society honored him with its Application Award. In 2012, he was honored by the IEEE Canada McNaughton Gold Medal and the Queen Elizabeth II Diamond Jubilee Medal. In 2013, he received the IEEE MTT-S Microwave Career Award "For a career of leadership, meritorious achievement, creativity and outstanding technical contributions in the field of microwave theory and techniques." Active in artistic endeavors, John has written a novel, a screenplay, and several stage plays, three of which have been performed, one of which he directed himself.