Design Optimization Via Surrogate Modeling And Space Mapping: The Why, The When, And The How

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The Space Mapping Team

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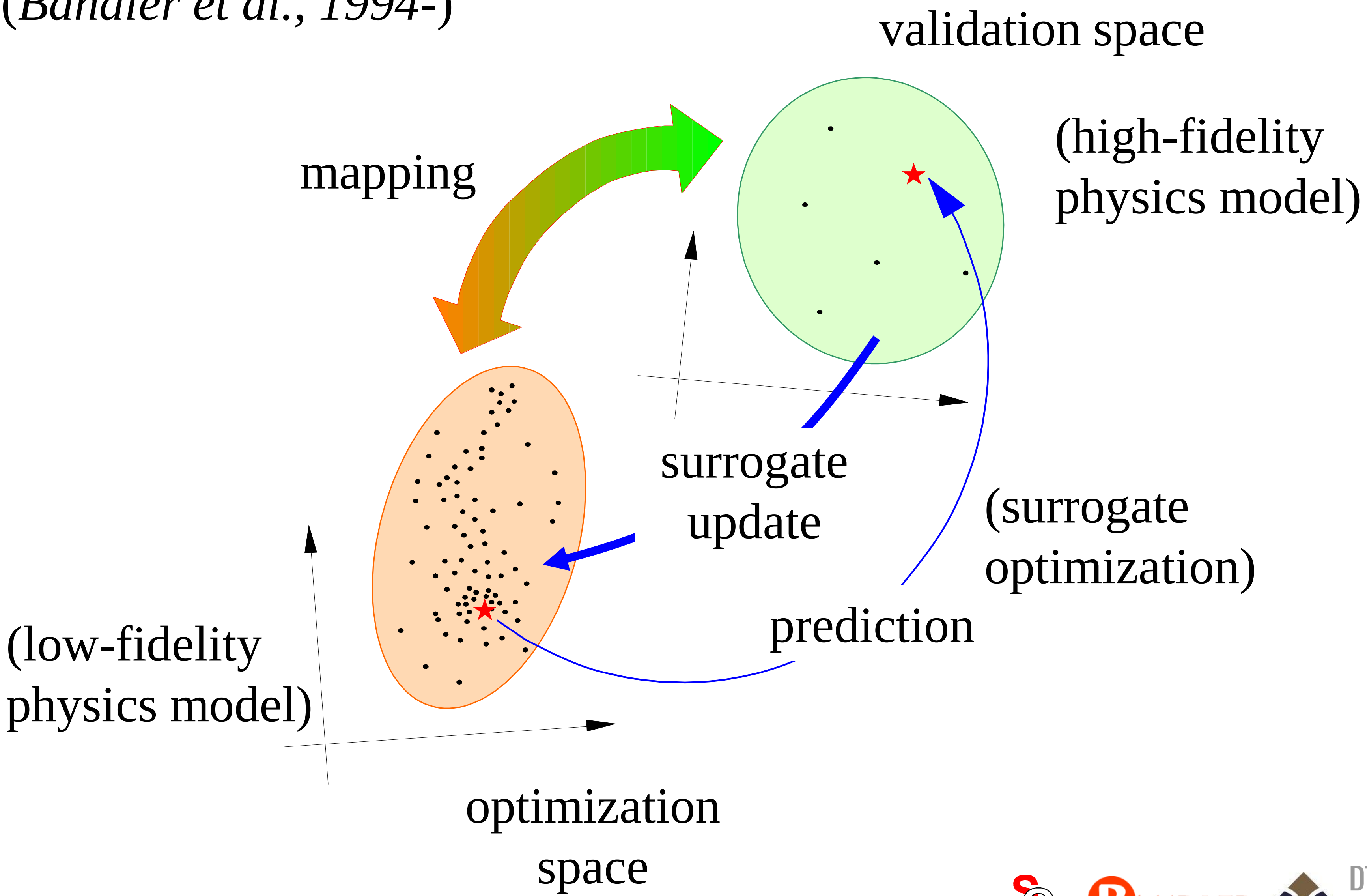
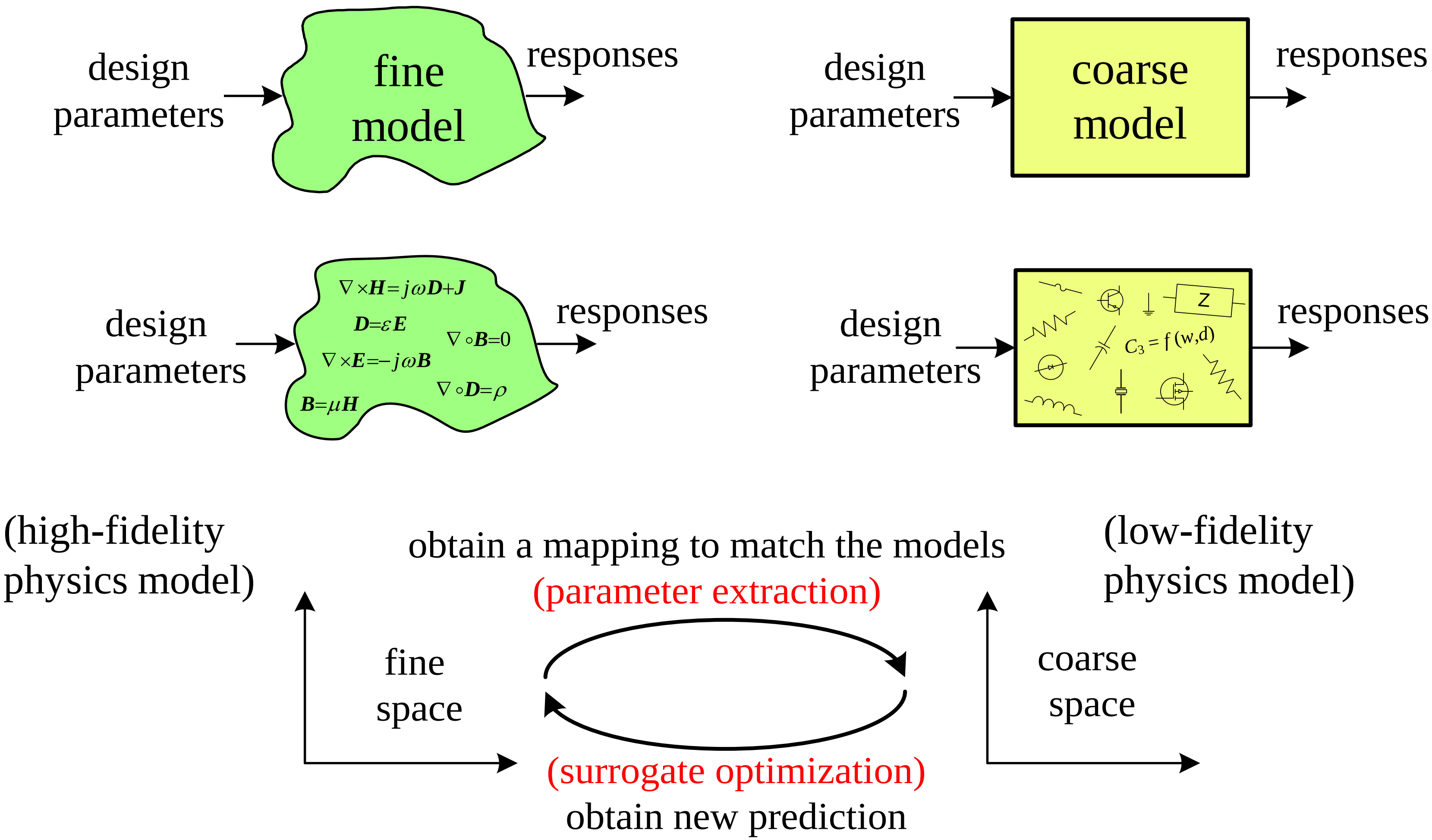
The Space Mapping Concept

(*Bandler et al., 1994-*)

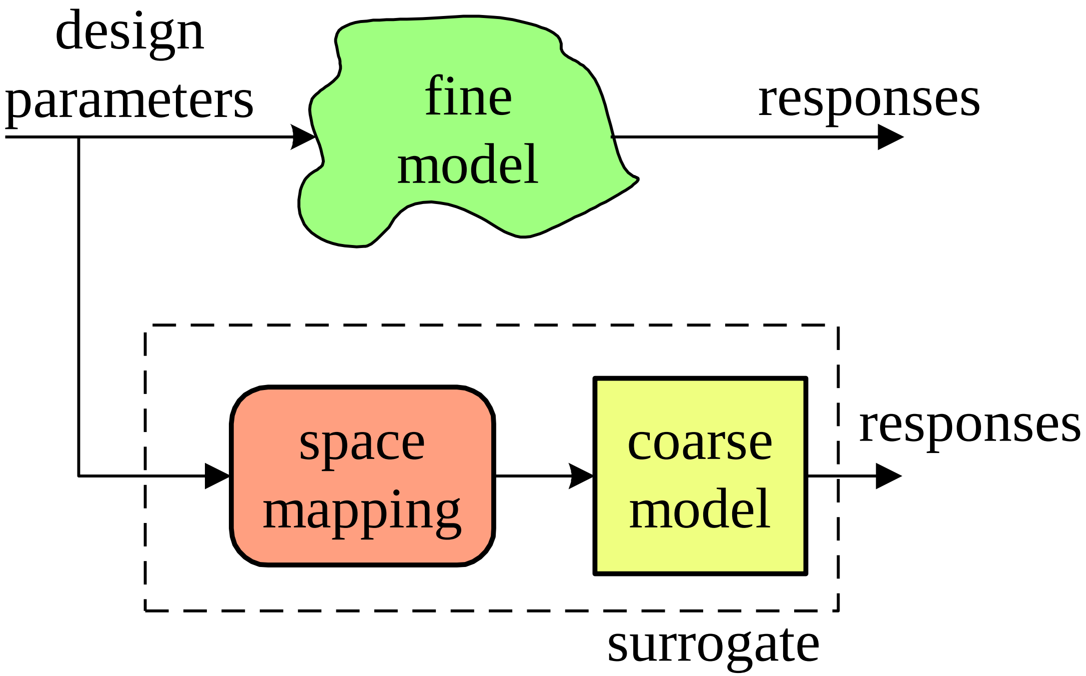


Linking Companion Coarse (Empirical) and Fine (EM) Models Via Space Mapping (*Bandler et al., 1994-*)



Explicit (Input) Space Mapping Concept

(*Bandler et al., 1994*-)



used in the microwave industry (e.g., Com Dev, since 2003, for optimization of dielectric resonator filters and multiplexers)

Aggressive Space Mapping Optimization
(*Bandler et al., 1995*)

corresponds to solving the nonlinear system of equations

$$\boldsymbol{f}(\boldsymbol{x}_f) \triangleq \boldsymbol{P}(\boldsymbol{x}_f) - \boldsymbol{x}_c^*, \quad \boldsymbol{f} \rightarrow \boldsymbol{0}$$

equivalently, “solve”

$$\boldsymbol{x}_c = \boldsymbol{x}_c^*$$

Aggressive Space Mapping **Optimization**

(*Bandler et al., 1995*)

iteratively solves the nonlinear system

$$\boldsymbol{f}(\boldsymbol{x}_f) = \boldsymbol{0}$$

the quasi-Newton step $\boldsymbol{h}^{(j)}$ in the fine space is given by

$$\boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)} = -\boldsymbol{f}^{(j)}$$

the next iterate

$$\boldsymbol{x}_f^{(j+1)} = \boldsymbol{x}_f^{(j)} + \boldsymbol{h}^{(j)}$$

Aggressive Space Mapping Optimization
(*Bandler et al., 1995*)

use the Broyden update

$$\boldsymbol{B}^{(j+1)} = \boldsymbol{B}^{(j)} + \frac{\boldsymbol{f}^{(j+1)} - \boldsymbol{f}^{(j)} - \boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)}}{\boldsymbol{h}^{(j)T}\boldsymbol{h}^{(j)}}\boldsymbol{h}^{(j)T}$$

Aggressive Space Mapping Optimization
(*Bandler et al., 1995*)

$$\boldsymbol{f}^{(j)} = \boldsymbol{x}_c^{(j)} - \boldsymbol{x}_c^{*} \,,$$

$$\boldsymbol{h}^{(j)} = \boldsymbol{x}_f^{(j+1)} - \boldsymbol{x}_f^{(j)} \text{ and}$$

$$\boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)} = -\boldsymbol{f}^{(j)}$$

estimate the fine model Jacobian (*Bakr et al., 1999*)

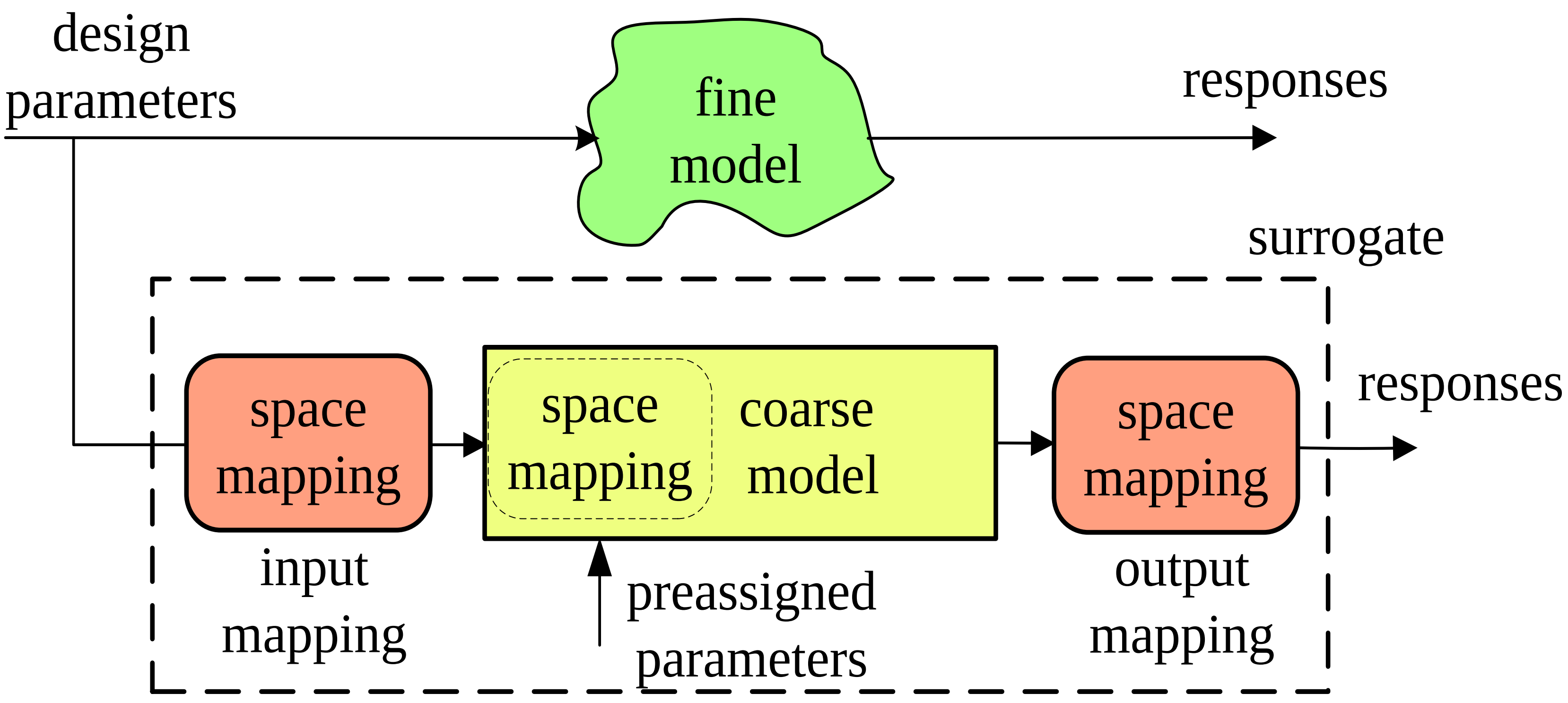
$$\boldsymbol{J}_f(\boldsymbol{x}_f) \approx \boldsymbol{J}_c(\boldsymbol{x}_c)\boldsymbol{B}$$

estimate the mapping matrix

$$\boldsymbol{B} \approx (\boldsymbol{J}_c^T \boldsymbol{J}_c)^{-1} \boldsymbol{J}_c^T \boldsymbol{J}_f$$

Space Mapping: Beware of … Imitations

Implicit, Input and Output Space Mappings
(*Bandler et al., 2003*-)



expert engineering knowledge helpful (few designable variables)

expertise helpful in "tuning the surrogate" (many possibilities, e.g., dielectric constant)

engineering expertise perhaps less necessary (many output variables)

The Novice-Expert Continuum

output space mapping: a "band-aid" solution for engineers and non-engineers; the parameter extraction step does not require coarse model re-analysis; good for final touch-ups

input space mapping: an engineering approach to find and cure the root-cause of a defect; but the parameter extraction step can be a difficult inverse optimization problem to solve w.r.t. the coarse model

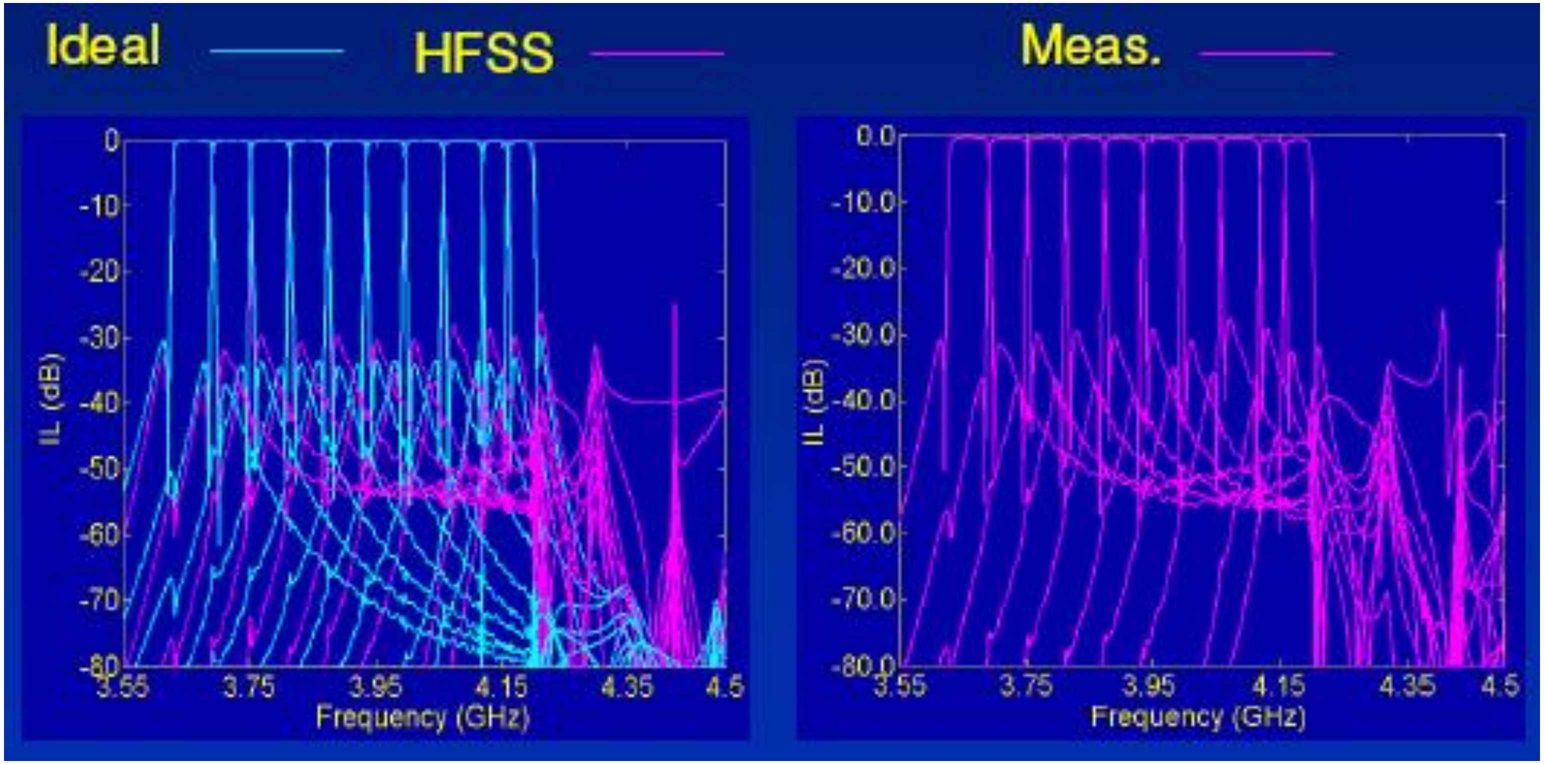
tuning space mapping (new): simulator-based expert approach

but all types of space mapping can be viewed as special cases of implicit space mapping

Space Mapping **Design of Dielectric Resonator Multiplexers**

(*Ismail et al., 2003, Com Dev, Canada*)

10-channel output multiplexer, 140 variables, aggressive SM



Space Mapping Crashworthiness Design of Saab 9[3]

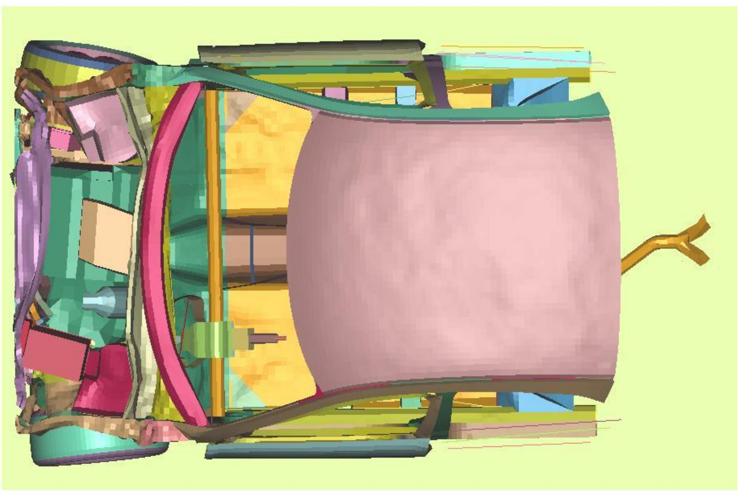
(*Redhe et al., 2001-2004, Sweden*)

[type "saab space mapping" into Google]

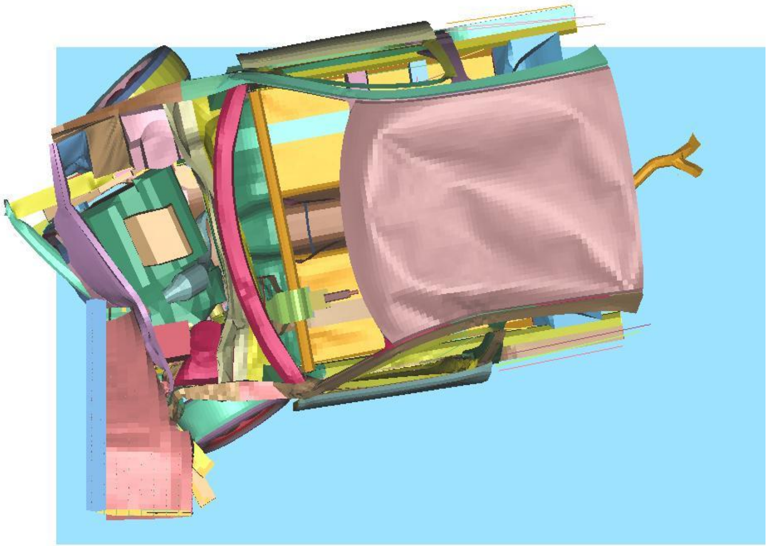
in crashworthiness finite element design, space mapping reduces the total computing time to optimize the vehicle structure more than 50% compared to traditional optimization

when space mapping was applied to the complete FE model of the new Saab 9[3] Sport Sedan, intrusion into the passenger compartment area after impact was reduced by 32% with no reduction in other crashworthiness responses

Space Mapping Crashworthiness Design of Saab 9^3 Frontal Impact (*Nilsson and Redhe, 2005, Sweden*)

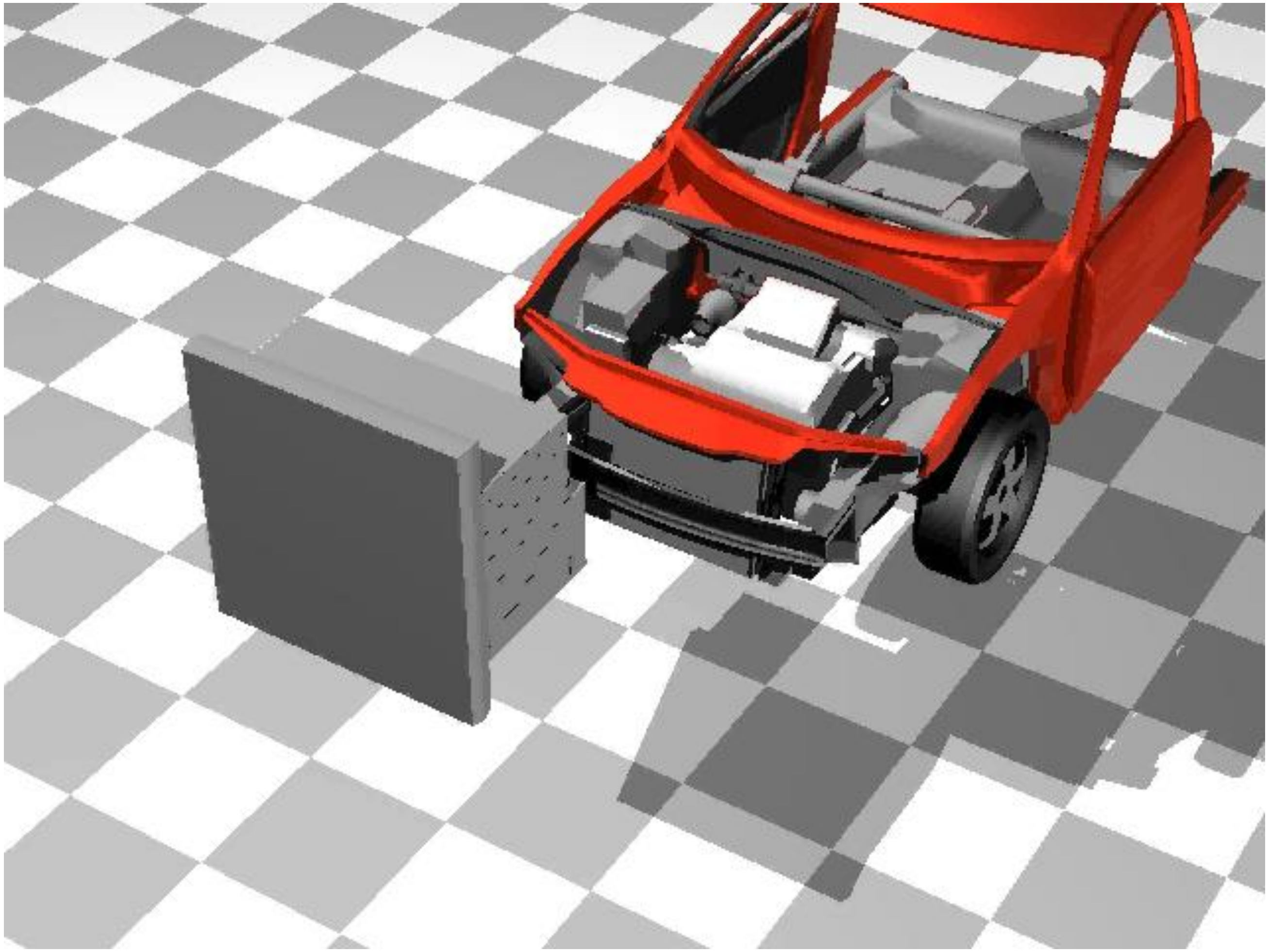


US-NCAP



EU-NCAP

Space Mapping Crashworthiness Design of Saab 9^3 Frontal Impact (*Nilsson and Redhe, 2005, Sweden*)



Space Mapping Crashworthiness Design of Saab 9[3]
(*www.studyinsweden.se, 2005*)

space mapping cuts calculation times by three fourths compared with traditional response surface optimization

driven straight into a steel barrier
at 56 km/h

penetration of the passenger space
was reduced by 32 percent

SMF: A <u>User-friendly</u> Space Mapping Software Engine

(*Bandler Corp., 2006, Koziel and Bandler, 2007*)

SMF: for SM-based constrained optimization, modeling and statistical analysis

to make space mapping accessible to engineers inexperienced in the art

to incorporate existing space mapping approaches in one package

implementation: a GUI based Matlab package

simulators sockets: Agilent ADS, Sonnet ***em***, FEKO, MEFiSTo, Ansoft Maxwell, Ansoft HFSS

SMF Uses a General Space Mapping Surrogate Model

surrogate model $\boldsymbol{R}_s^{(i)}$ at iteration i

$$\boldsymbol{R}_s^{(i)}(\boldsymbol{x}) = \boldsymbol{A}^{(i)} \cdot \boldsymbol{R}_c(\boldsymbol{B}^{(i)} \cdot \boldsymbol{x} + \boldsymbol{c}^{(i)}, \boldsymbol{G}^{(i)} \cdot \boldsymbol{x} + \boldsymbol{x}_p^{(i)}) + \boldsymbol{d}^{(i)} + \boldsymbol{E}^{(i)} \cdot (\boldsymbol{x} - \boldsymbol{x}^{(i)})$$

where $\boldsymbol{A}^{(i)}$, $\boldsymbol{B}^{(i)}$, $\boldsymbol{c}^{(i)}$, $\boldsymbol{x}_p^{(i)}$ and $\boldsymbol{G}^{(i)}$ are determined using parameter extraction

$$(\boldsymbol{A}^{(i)}, \boldsymbol{B}^{(i)}, \boldsymbol{c}^{(i)}, \boldsymbol{x}_p^{(i)}, \boldsymbol{G}^{(i)}) = \arg \min_{(\boldsymbol{A},\boldsymbol{B},\boldsymbol{c},\boldsymbol{x}_p,\boldsymbol{G})} \sum_{k=0}^{i} w_k \,\| \boldsymbol{R}_f(\boldsymbol{x}^{(k)}) - \boldsymbol{A} \cdot \boldsymbol{R}_c(\boldsymbol{B} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{c}, \boldsymbol{G} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{x}_p) \| + \sum_{k=0}^{i} v_k \,\| \boldsymbol{J}_{\boldsymbol{R}_f}(\boldsymbol{x}^{(k)}) - \boldsymbol{J}_{\boldsymbol{R}_s}(\boldsymbol{B} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{c}, \boldsymbol{G} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{x}_p) \|$$

and

$$\boldsymbol{d}^{(i)} = \boldsymbol{R}_f(\boldsymbol{x}^{(i)}) - \boldsymbol{A}^{(i)} \cdot \boldsymbol{R}_c(\boldsymbol{B}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{c}^{(i)}, \boldsymbol{G}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{x}_p^{(i)})$$

$$\boldsymbol{E}^{(i)} = \boldsymbol{J}_{\boldsymbol{R}_f}(\boldsymbol{x}^{(i)}) - \boldsymbol{J}_{\boldsymbol{R}_s}(\boldsymbol{B}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{c}^{(i)}, \boldsymbol{G}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{x}_p^{(i)})$$

Space Mapping Theory and Applications

Bandler, since 1994, on space mapping:
http://www.sos.mcmaster.ca/lifepubs.htm

space mapping bibliography:
http://www.sos.mcmaster.ca/referen.htm

and . . .

how I got addicted to space mapping (*Snel*, *2006*)

and . . .

Some Recent Space Mapping Applications 8: November 2006

17 relevant presentations (out of 33) at
Second Int. Workshop on Surrogate Modelling and Space Mapping for Engineering Optimization,
Bandler and Madsen, Co-Organizers,
Technical University of Denmark, Nov. 9-11, 2006.
http://www2.imm.dtu.dk/~km/smsmeo-06/

4 relevant presentations (out of 8) at Space-Mapping Day,
Workshop on Space-Mapping and Efficient Optimization,
Centre for Mathematics and Computer Science (CWI),
Amsterdam, The Netherlands, Nov. 13, 2006.
http://www.cwi.nl/events/2006/spacemapping.html

So Why Does Space Mapping Work?

because **space mapping** is a natural mechanism for the brain to relate objects or images with other objects, images, reality, or experience

“experienced” engineering designers (experts), knowingly or not, routinely employ (or have employed) **space mapping**
to achieve complex designs

with virtually no mathematics, simple everyday examples illustrate **space mapping**, e.g., archery, stone-throwing, cheese-cutting, log-cutting, cake-cutting, shoe-selection, . . .

space mapping offers a quantitative explanation for the engineer’s mysterious “feel” for a problem

The Brain's Automatic Pilot
(*Sandra Blakeslee, The New York Times,*
International Herald Tribune, February 21, 2002, p.7)

[certain brain] circuits are used by the human brain
to assess social rewards …

…findings [by neuroscientists] …challenge the notion
that people always make conscious choices
about what they want and how to obtain it.

Gregory Berns (Emory University School of Medicine):
… most decisions are made subconsciously
with many gradations of awareness.

The Brain's Automatic Pilot
(*Sandra Blakeslee, The New York Times,*
International Herald Tribune, February 21, 2002, p.7)

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 brain has evolved to shape itself, starting in infancy, according to what it encounters in the external world.

… much of the world is predictable: buildings usually stay in one place, gravity makes objects fall …

The Brain’s Automatic Pilot
(*Sandra Blakeslee, The New York Times,*
International Herald Tribune, February 21, 2002, p.7)

As children grow, their brains build internal models [coarse, surrogate] of everything they encounter, gradually learning to identify objects …

… as new information flows into it [fine model data] … the brain automatically compares it [par. 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].

Drawing on past experience [expert knowledge] … a decision [prediction] is made …

Bandler's Conjecture No. 1

space mapping is a natural mechanism for the brain to relate objects or images with other objects, images, reality, or experience

Bandler's Conjecture No. 2

brains of "clever", experienced or intuitive individuals employ a Broyden-like update in the space mapping process

Bandler's Conjecture No. 3

"experienced" engineering designers, knowingly or not, routinely employ space mapping to achieve complex designs

Bandler's Proposal No. 1

neuroscientific experiments on human subjects:
do our brains really use space mapping every day?

Bandler's Proposal No. 2

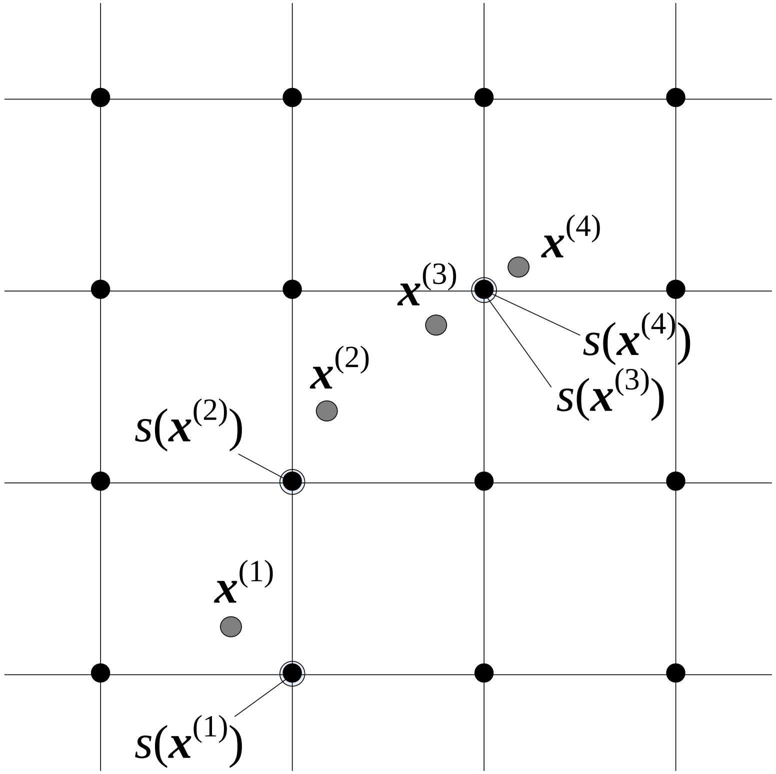
commercial engineering simulators: engineered or reengineered
to reflect the known utility of space mapping

Bandler's Proposal No. 3

the undergraduate curriculum should include
space mapping as a fundamental design and modeling tool

Space-Mapping-Based Interpolation (*Koziel et al., 2006*)

assumption: the fine model is available on a structured grid



define an interpolated fine model as

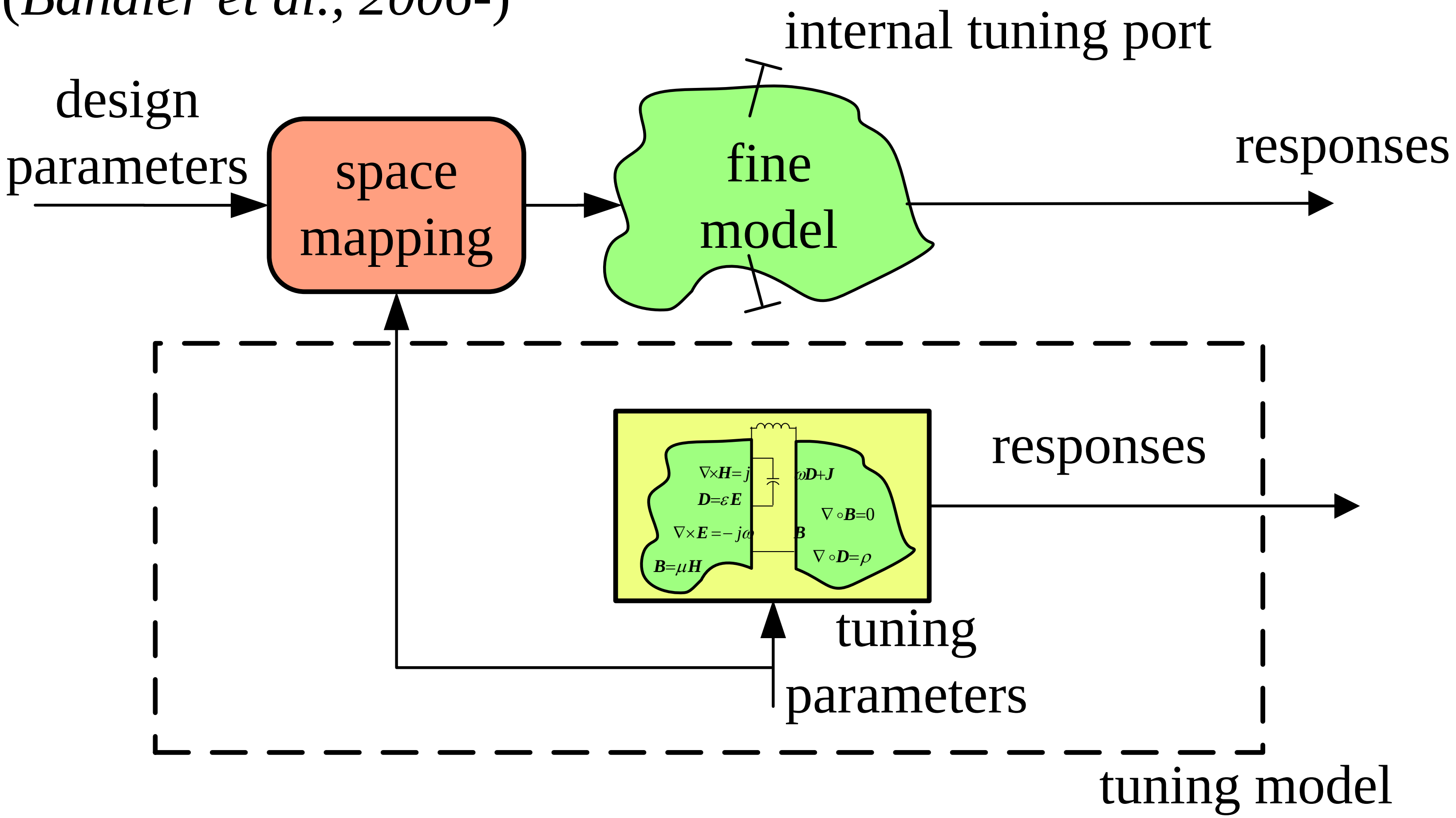
$$\bar{\boldsymbol{R}}_f(\boldsymbol{x}^{(i+1)}) = \boldsymbol{R}_f(s(\boldsymbol{x}^{(i+1)})) + \\ + \boldsymbol{R}_s^{(i)}(\boldsymbol{x}^{(i+1)}) - \boldsymbol{R}_s^{(i)}(s(\boldsymbol{x}^{(i+1)}))$$

where snapping function *s*(.) is defined as

$$s(\boldsymbol{x}) = \left\{ \bar{\boldsymbol{x}} \in \bar{X}_f : \|\boldsymbol{x} - \bar{\boldsymbol{x}}\| = \min_{\boldsymbol{z}\in\bar{X}_f} \|\boldsymbol{z} - \bar{\boldsymbol{x}}\| \ \wedge \forall_{\boldsymbol{y}=\arg\min_{\boldsymbol{z}\in\bar{X}_f}\|\boldsymbol{z}-\bar{\boldsymbol{x}}\|,\ \boldsymbol{y}\neq\bar{\boldsymbol{x}}} \ \bar{\boldsymbol{x}} \prec \boldsymbol{y} \right\}$$

For the Expert: Tuning Space Mapping (TSM)

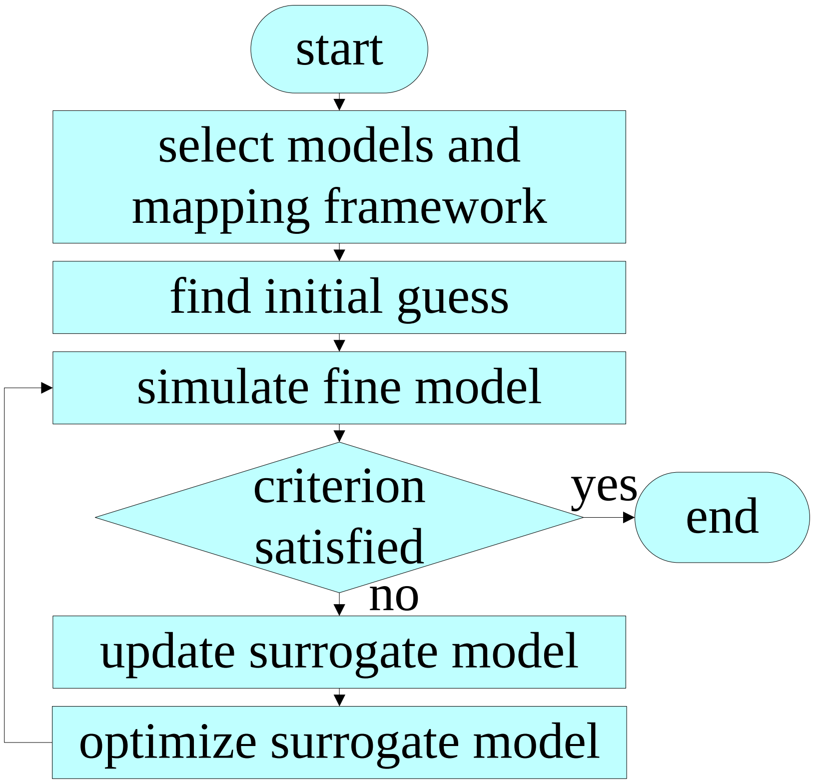
(*Bandler et al., 2006-*)



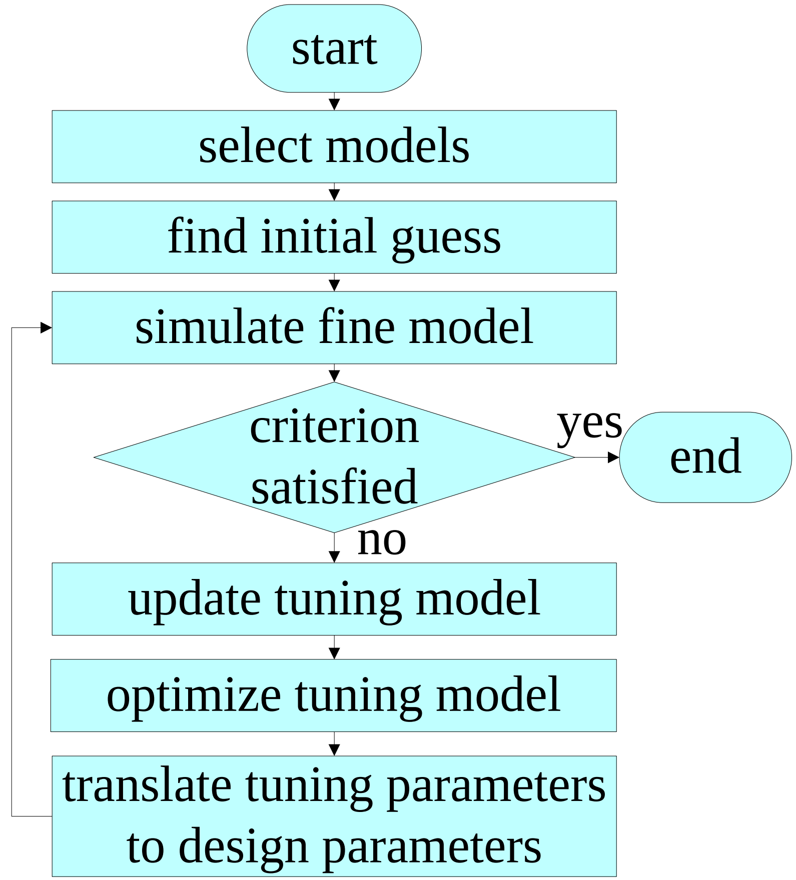
surrogate based on the fine model with internal tuning ports

Tuning Space Mapping (TSM) Flowchart

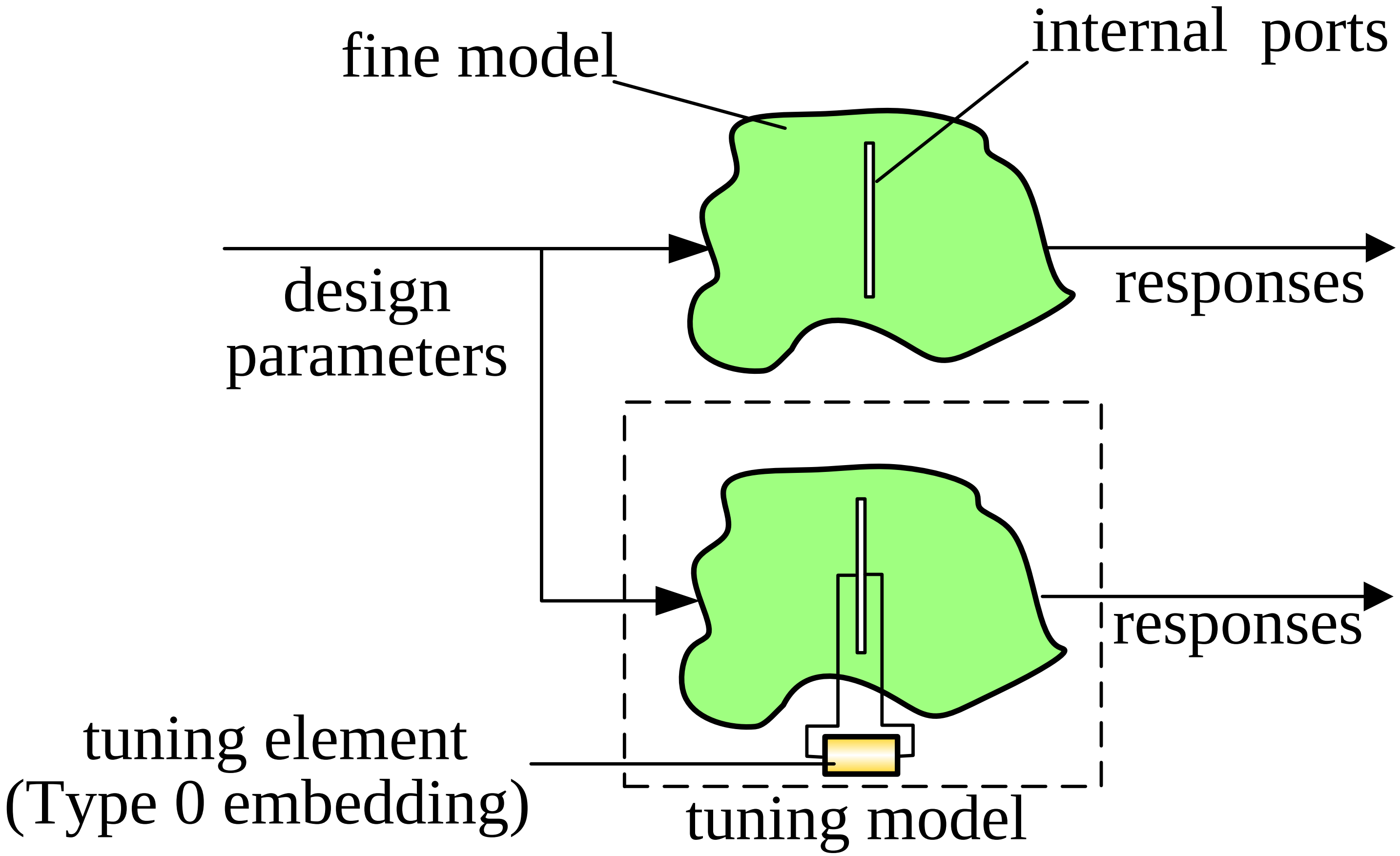
Classical Space Mapping
(*Bandler et al., 2004*)



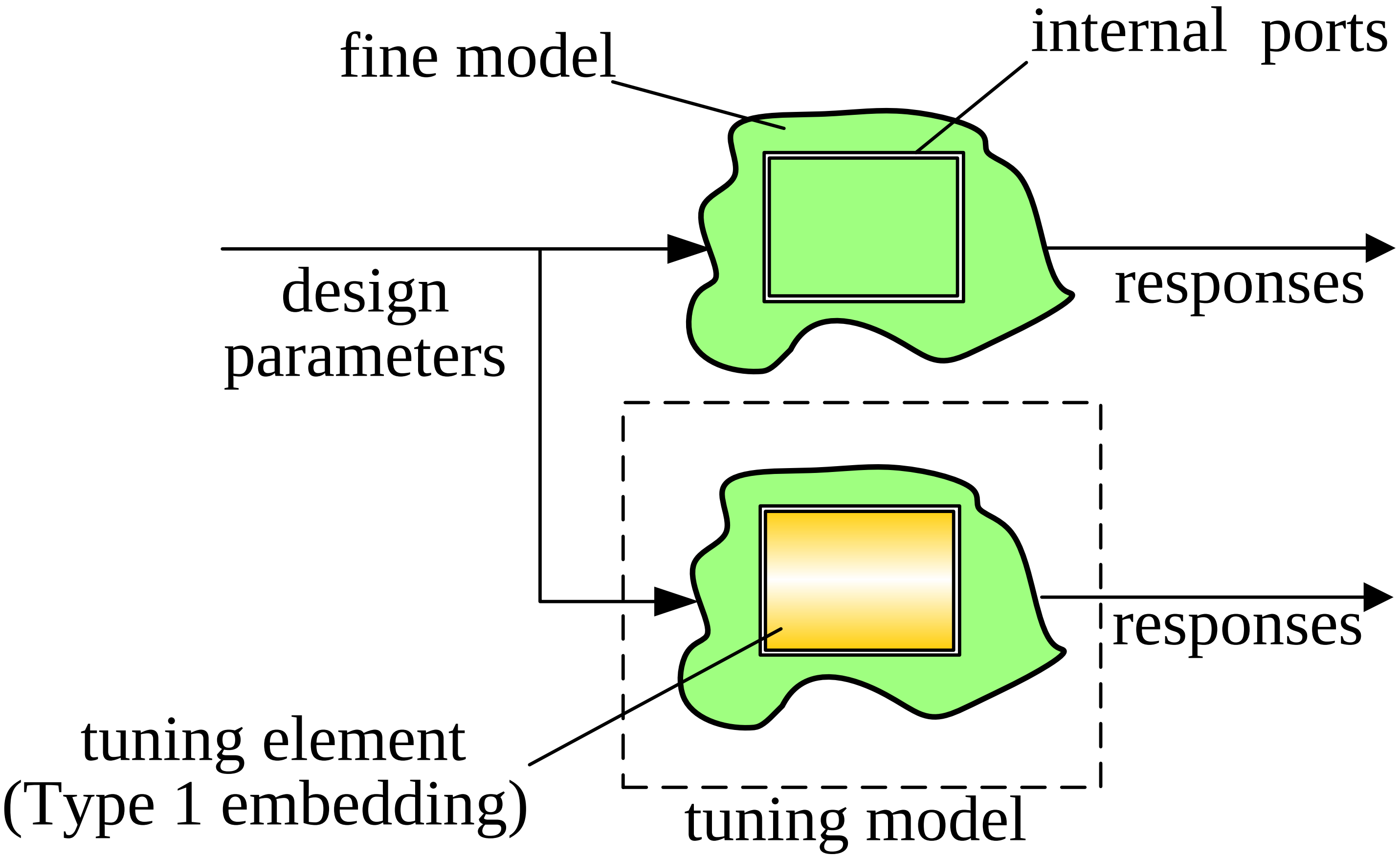
Tuning Space Mapping
(*Koziel et al., 2008*)



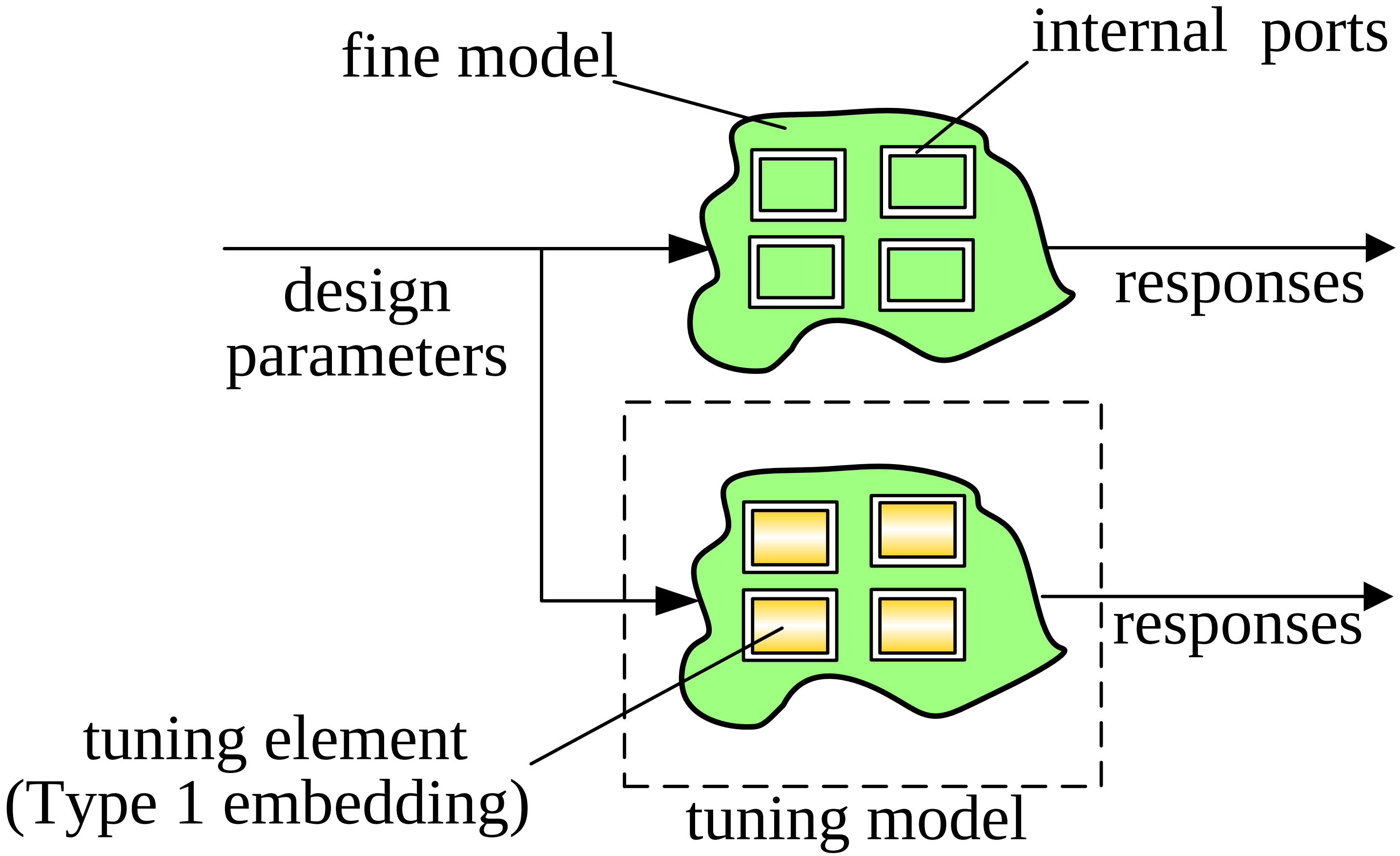
Tuning Space Mapping (TSM): Type 0 Embedding



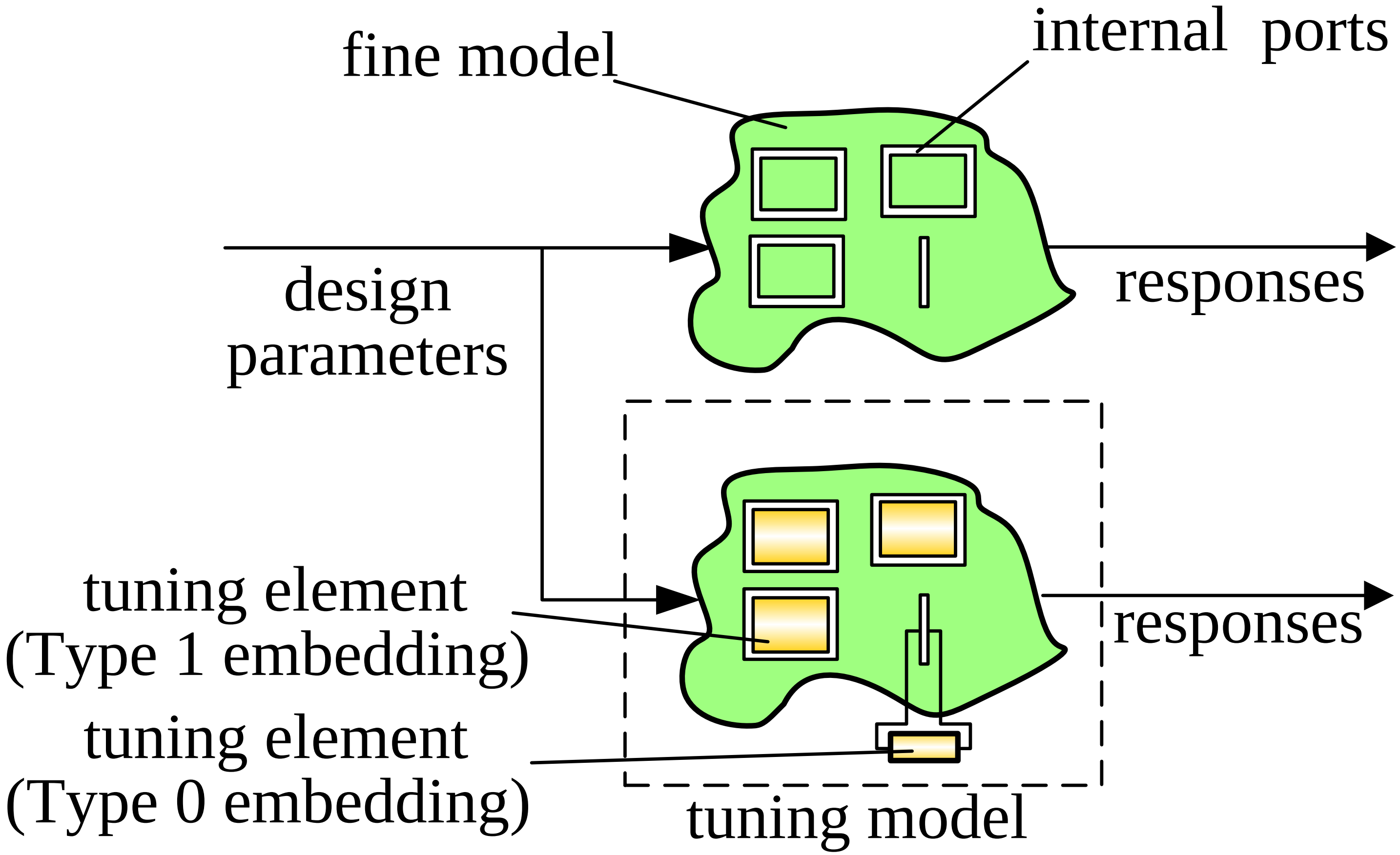
Tuning Space Mapping (TSM): Type 1 Embedding



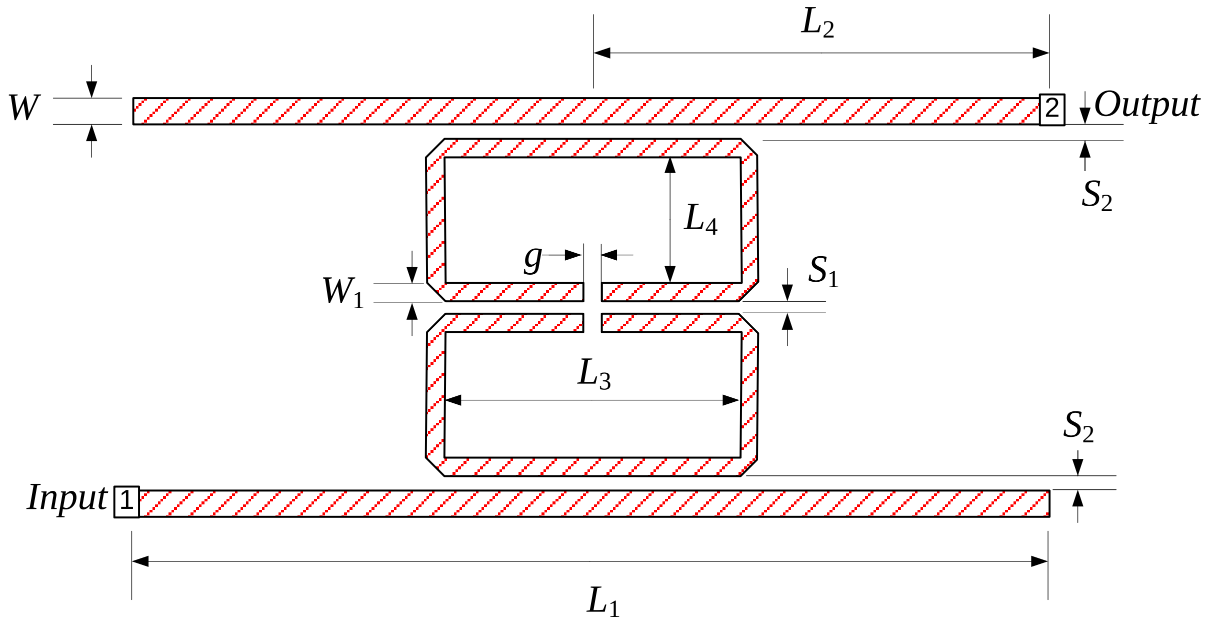
Tuning Space Mapping (TSM): Type 1 Embedding



Tuning Space Mapping (TSM): Type 1 and Type 0 Embedding



Open-loop Ring Resonator Bandpass Filter (*Koziel et al., 2008*)



design parameters

$\boldsymbol{x} = [L_1 \;\; L_2 \;\; L_3 \;\; L_4 \;\; S_1 \;\; S_2 \;\; g]^T$ mm

specifications

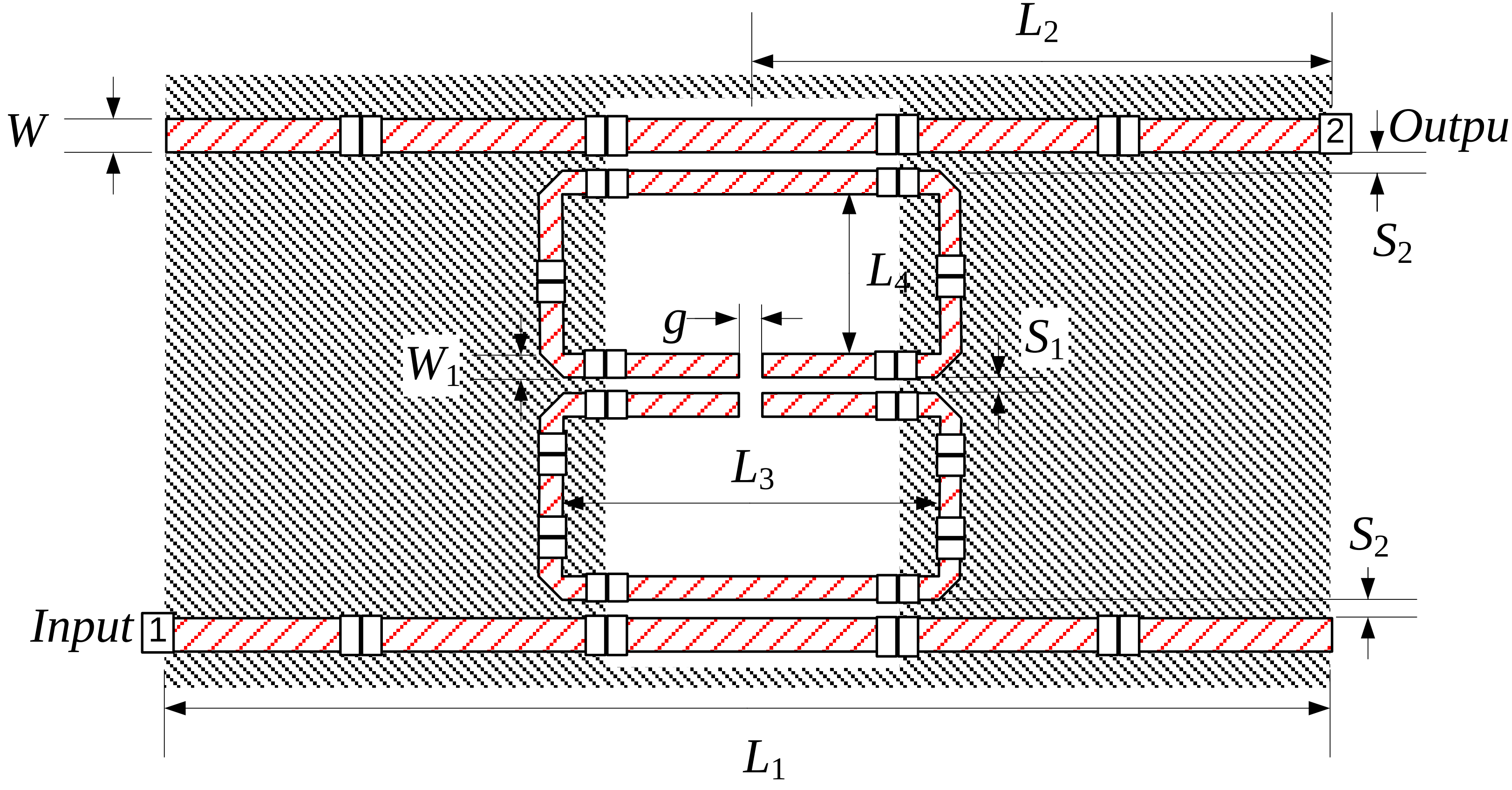
$|S_{21}| \geq -3$ dB for 2.8 GHz $\leq \omega \leq$ 3.2 GHz

$|S_{21}| \leq -20$ dB for 1.5 GHz $\leq \omega \leq$ 2.5 GHz

$|S_{21}| \leq -20$ dB for 3.5 GHz $\leq \omega \leq$ 4.5 GHz

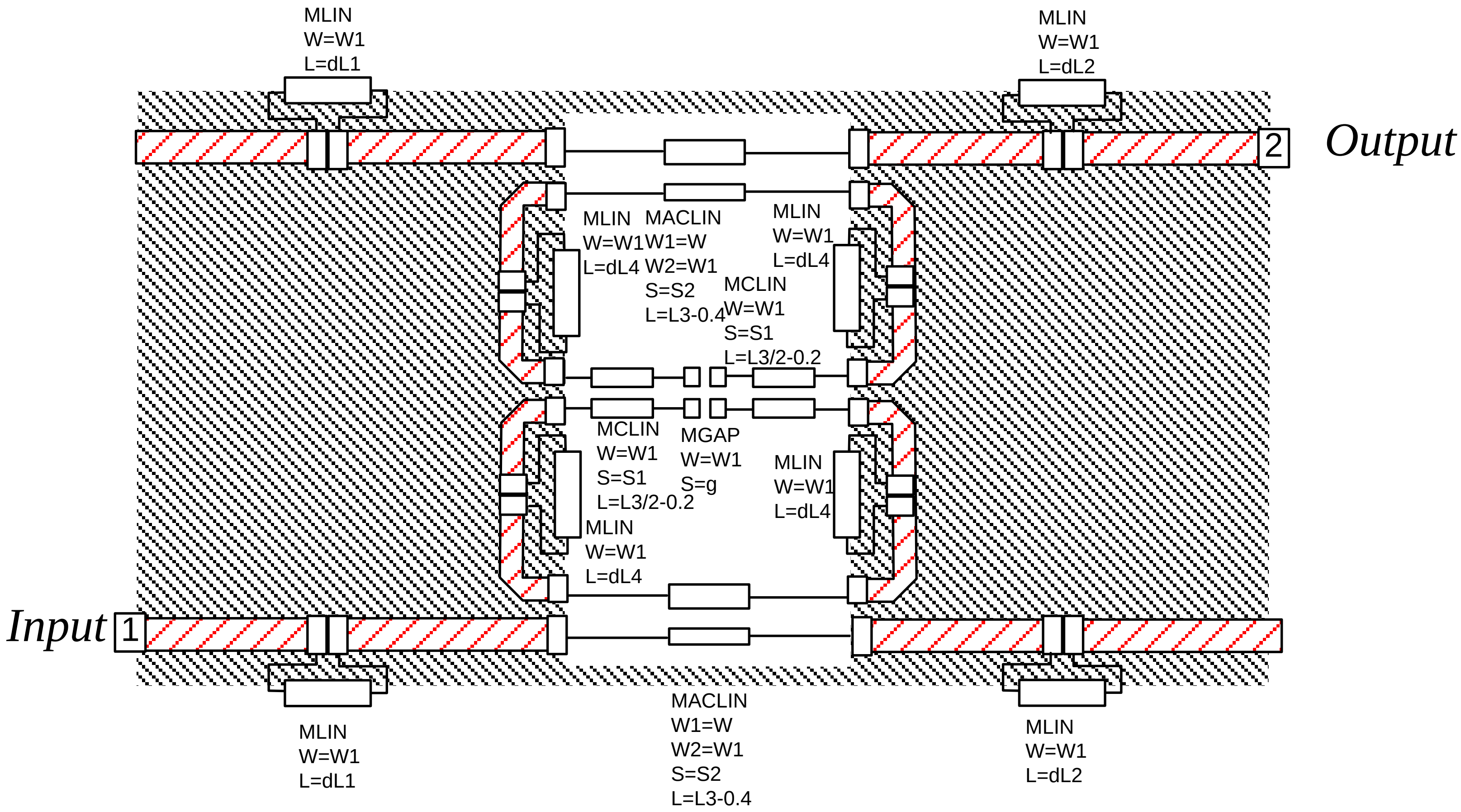
Open-loop Ring Resonator Bandpass Filter (Type 1 and Type 0)

Sonnet ***em*** model with internal (co-calibrated) ports



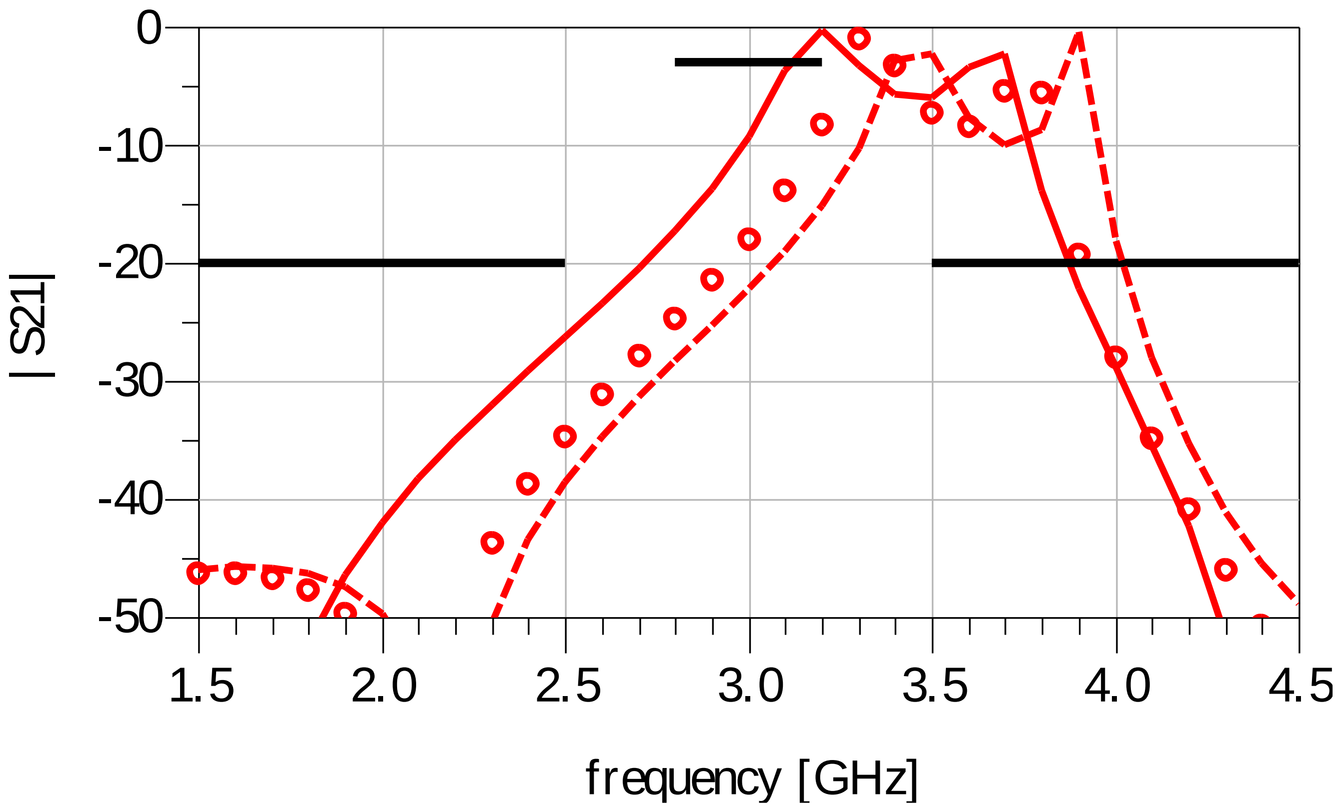
Open-loop Ring Resonator Bandpass Filter (Type 1 and Type 0)

Sonnet ***em*** model with internal (co-calibrated) ports



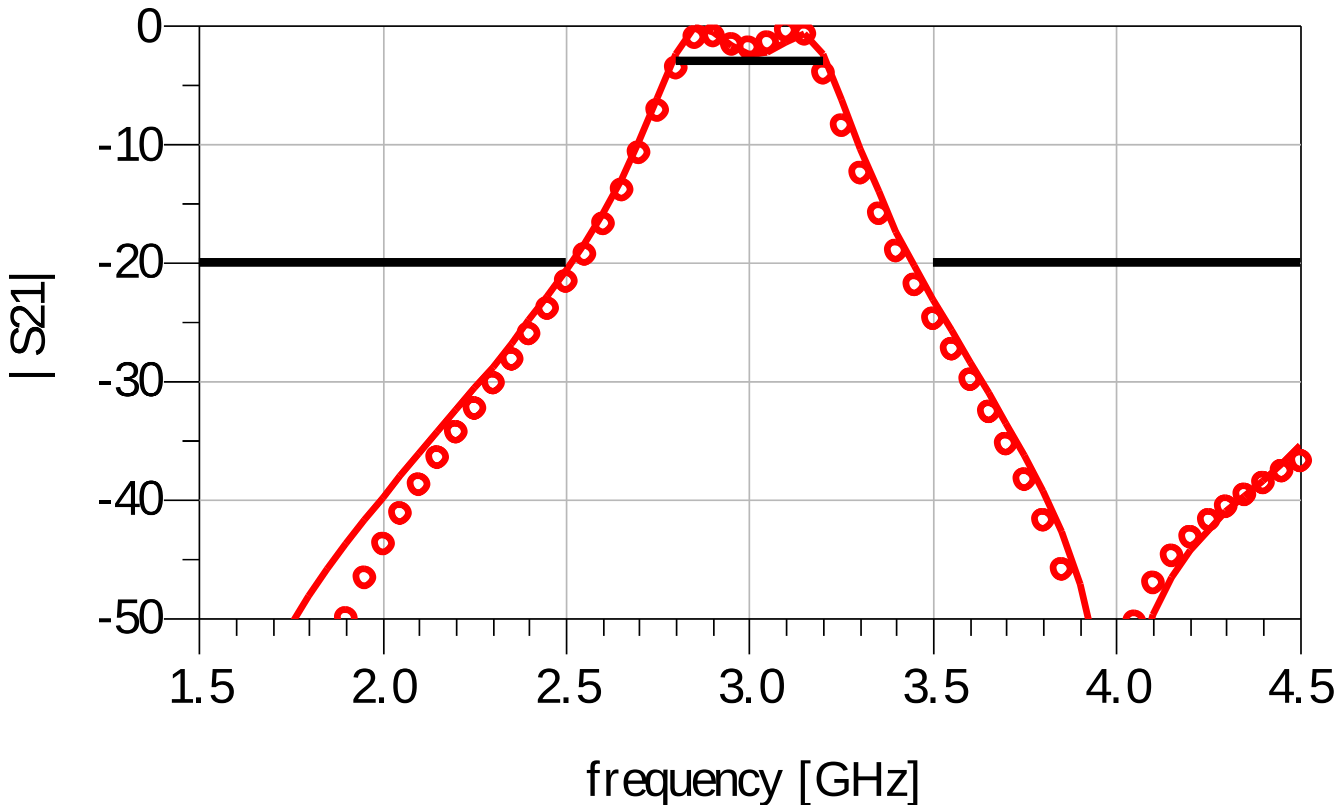
Open-loop Ring Resonator Bandpass Filter (Type 0 and Type 1)

initial responses: tuning model (—), fine model (○), fine model with co-calibrated ports (---)



Open-loop Ring Resonator Bandpass Filter (Type 0 and Type 1)

responses after two iterations: the tuning model (—), corresponding fine model (○)



Tuning Space Mapping with Embedded Surrogate Elements

physically-based surrogate element embedding technique to facilitate simulator-based tuning design

the tuning model is embedded with fine-model couplings and discontinuity information, and aligned with the fine model

direct access to the physical design parameters

avoids negative tuning parameter values

effectively solves the problem of cross-sectional parameter design

Space Mapping Technology: Our Current Work

new SM frameworks, SM modeling techniques, SM optimization algorithms, software, convergence proofs, . . .

antennas, microwaves, inverse problems, electromagnetic modeling and design (with Bakr and Nikolova, McMaster)

methodologies for electronic device and component model enhancement (with Q.J. Zhang, Carleton University)

space mapping within Agilent ADS (with Q.S. Cheng, McMaster)

tuning space mapping (with Cheng, Rautio, Koziel)