Industrial Challenges in Circuit Simulation : 2002-2010

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Today’s Questions:

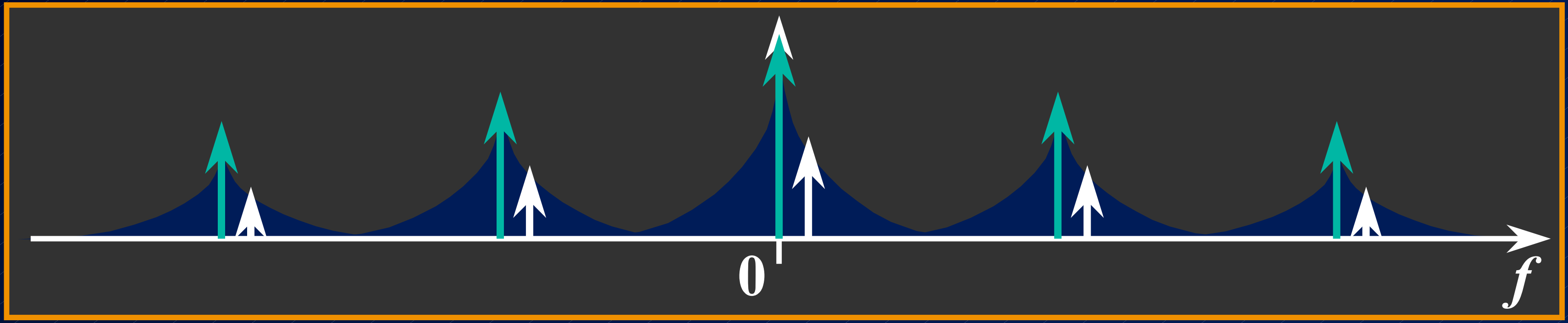
What are the open problems in circuit simulation? Where are the opportunities to have an impact on industry?

Personal View of 1990s

- Market Driver : Wireless Communications
  - RF simulation becomes mainstream
- Technology Driver : Deep-Submicron Integrated Circuit Processes
  - Local parasitics are important
- New (Enabling) Numerical Technology : Krylov-subspace methods
  - Full-Chip RF simulation
  - Model reduction for circuit, signal-integrity analysis

Example 1 : RF Circuit Simulation

- Multiple Timescale Problems
  - Carrier : 1 GHz
  - Voice/Data : 10-100kHz
- RF systems are designed to shift frequencies
- Intrinsically nonlinear, time-varying→ confusing

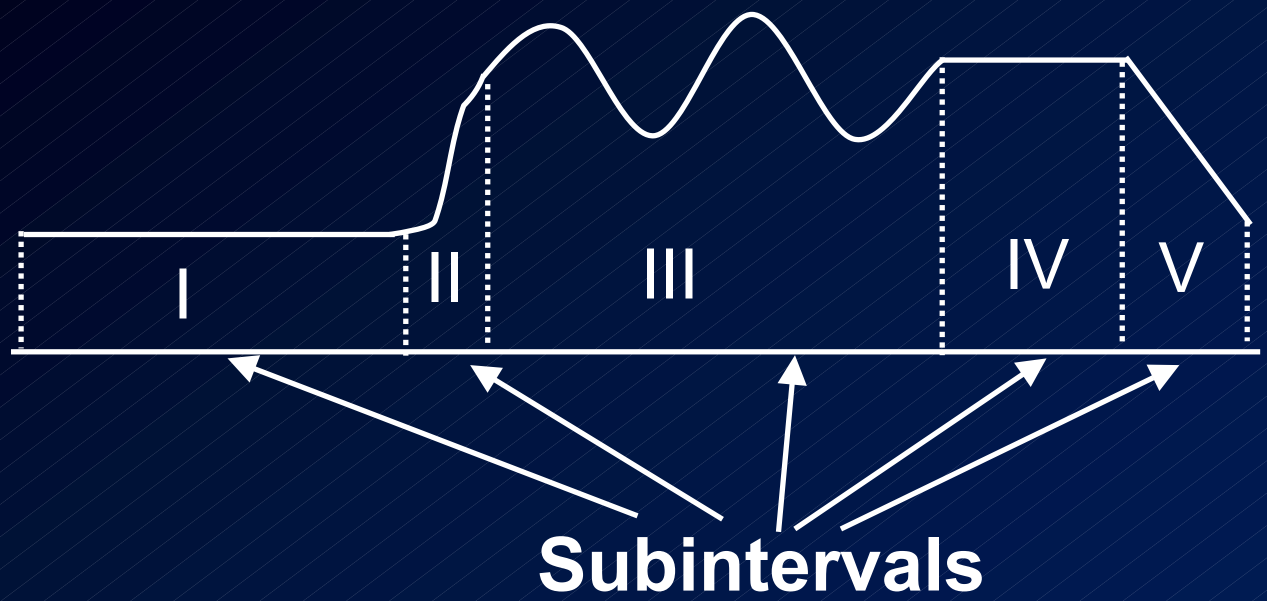


Example 1: RF Circuit Simulation

- Dedicated tools provide value for designers
  - Steady-state methods trade equations for insight
  - A good trade if you can solve lots of equations fast
- Before : Spectral methods (harmonic balance)
  - Good match to microwave design, linear circuits, traditional RF performance metrics
- Alternative : Shooting methods
  - Good match to existing circuit simulators, strongly nonlinear models
  - Very robust
  - Lack dynamic range; frequency-domain modeling is hard

Multiple Timescale Problems

- Multi-Interval Chebyshev-based method : continuum between spectral and Gear



High order where smooth, low order where irregular ; helps w/ linear, nonlinear convergence also! *And we can use frequency-domain models.*

Predictions

1990s

- Communications Driver
  - Narrowband
  - 1-5GHz
- Digital DSM ICs
  - Local Parasitics
  - Managing Scale
- Analysis Focus
  - Simulation

2000+

- Still Communications
  - Wideband

Multiple Timescale Problems

- Open problem : unstructured (marginal “carrier”) systems.
  - Frequency synthesis
  - Clock & data recovery
- Challenge : noise analysis
  - At transistor-level (accurate)
  - In time comparable to steady-state methods
  - With a supporting analysis framework
- Key numerical technology : ???

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High-Frequency Modeling

- Distributed effects become relevant for AMS ICs somewhere above 5GHz
- Challenge : Circuit model generation from integral equation codes

Lumped Linear Systems

- State-space models, input u , output y

$$\frac{dx}{dt} = Ax + Bu \qquad y = Cx + Du$$

- Frequency domain form

$$sx = Ax + Bu \qquad y = Cx + Du$$

$$H(s) = D + C(sI - A)^{-1}B \qquad y(s) = H(s)u(s)$$

Model reduction : in a rigorous manner, generate a system of the same form, but smaller dimension, with input-output behavior approximately the same

Distributed Linear Systems

- State-space models, input u, output y

$$sx = A(s)x + Bu \qquad y = Cx + Du$$

$$H(s) = D + C(sI - A(s))^{-1}B \qquad y(s) = H(s)u(s)$$

- High-frequency problems produce frequency-dependent $A(s)$
  - full-wave integral equation solvers
  - solvers with substrate interactions

Passivity

- Passive systems do not generate energy. We cannot extract out more energy than is stored. A passive system does not provide energy that is not in its storage elements.

$$\text{Energy} = \int_{-\infty}^{t} i(\tau) v(\tau)\, d\tau \geq 0$$

- Strictly passive systems dissipate energy and satisfy

$$\text{Energy} = \int_{-\infty}^{t} i(\tau) v(\tau)\, d\tau > 0$$

- If the reduced model is not passive it can generate energy from nothingness and the simulation will explode

Causality

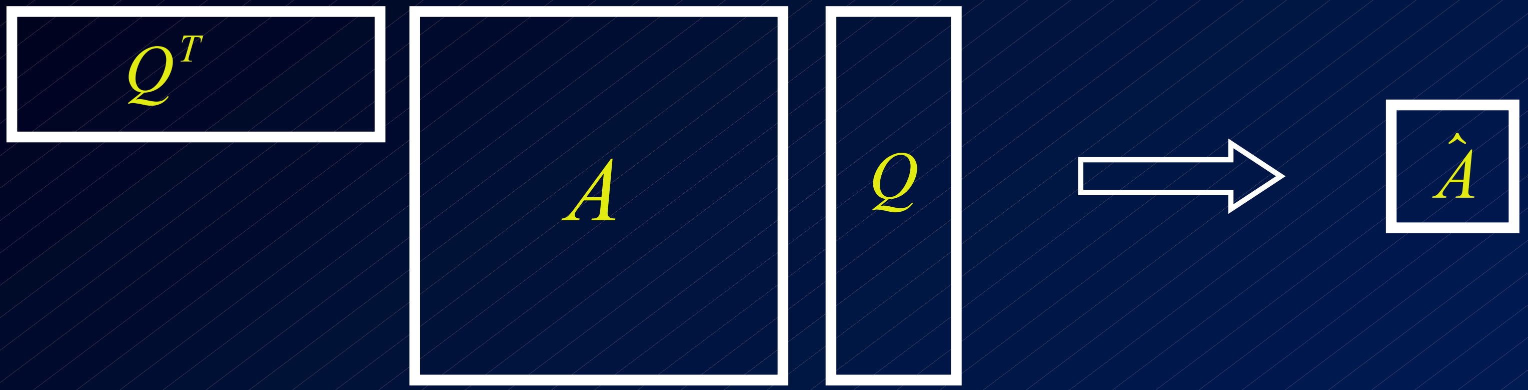
- We further suppose our systems have a convolutional representation

$$y(t) = \int_{-\infty}^{t} h(t-\tau)u(\tau)d\tau$$

- A causal system is not anticipative
  - present outputs depends on past inputs, not on future inputs $h(t) = 0 \qquad t < 0$

Projection methods for linear systems

- Projection squashes matrices to smaller size



- How to get Q ? How to represent $A(s)$?

  Projection must match frequency response

Our Procedure

1) Projection: from matrices of size ~100,000 frequency dependent, to size ~20 still frequency dependent

2) Interpolation: captures frequency dependency with *globally uniformly convergent rational approximant*

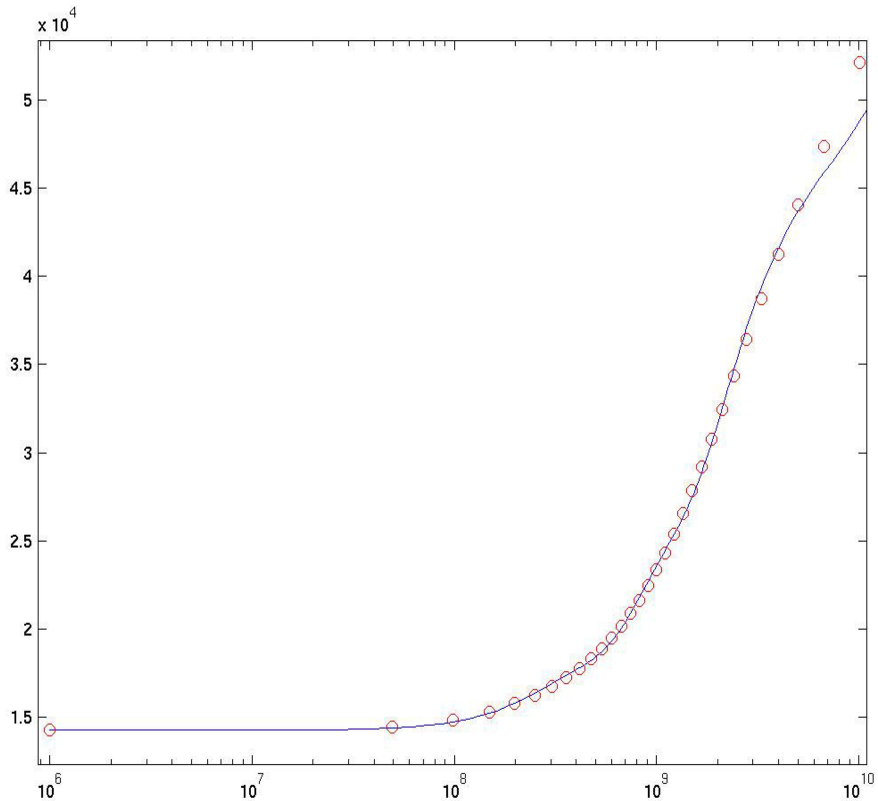
3) Realization of a reduced dynamical linear system

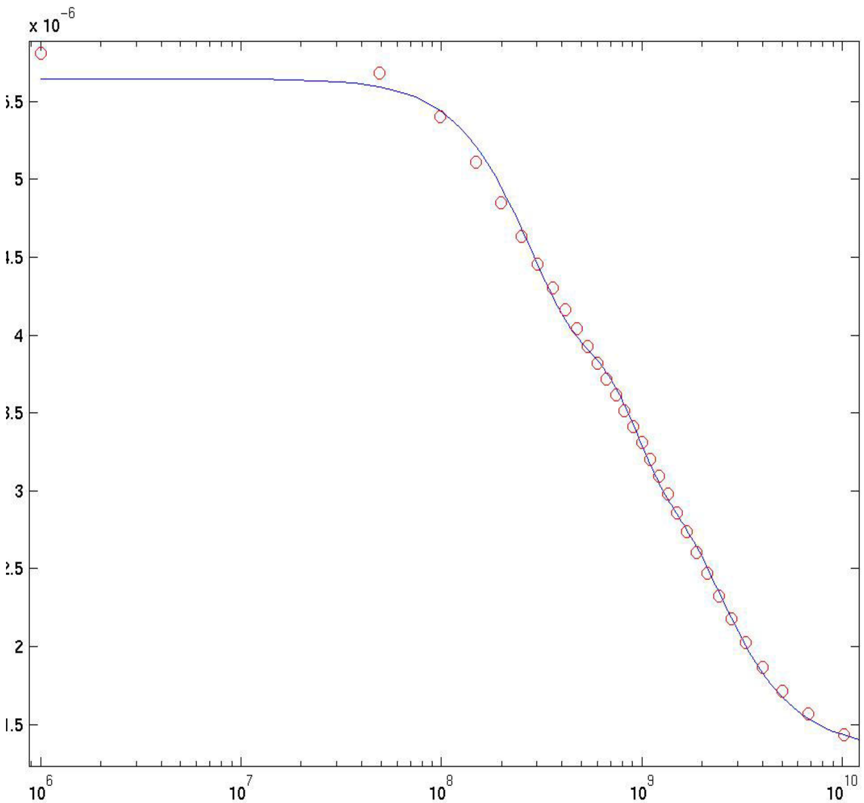
- can do this because the interpolation functions are rational

4) Passivity check + further reduction

Step 3: Realization (example)

- Real part of frequency response
- Inductive part of frequency response





High-Frequency Modeling

- Our procedure : distributed → lumped
- What about : distributed → distributed ?

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  - Global parasitics

Global Parasitic Analysis

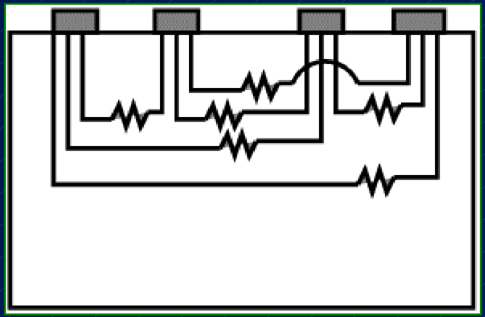
- Trend in analog/RF/mixed-signal circuit design :
  - Put everything together (integrate)!
  - Systems-on-chip, systems-in-package
  - Single-chip RF
  - Digital + analog together
- Integration is *good* because it reduces cost
  - (fewer parts)
- Integration is *bad* because it reduces isolation
  - (fewer parts)

Most Problematic Areas

- Ultra-sensitive systems
  - RF designs : very low input signal levels, high gain through signal path
  - Small unanticipated effects can degrade performance, stability
  - Need extreme (~120 dB) isolation
- Massive Coupling
  - Everything couples to every thing else : matrices are *potentially* dense or nearly so
    - Substrate networks
    - Package inductances
  - Computationally intractable except for tiny circuits

Key Questions for Massive Parasitic Models

- Q1: Do we really need to model all those couplings?
  - If not, how many do we need?
- Q2: If many, how to analyze them?
  - How to represent dense parasitic models?
  - How to extract?
  - How to simulate?
  - [Multi-level representations will play a key role.]
- Model problem: substrate analysis
  - Resistances only



Two Approaches to Substrate Analysis

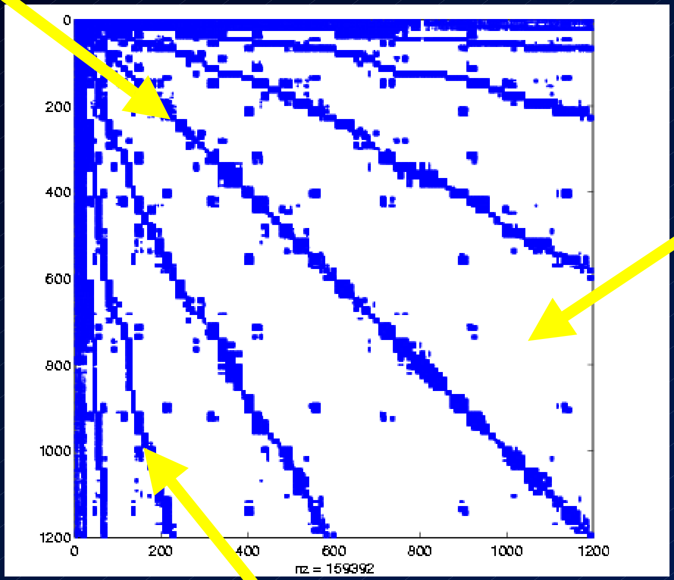
- Full Numerical Approach :
  - Throw the problem to a field solver
  - Wait a long time and get a big resistance matrix
  - Take the whole network and feed it to a circuit simulator
- Heuristic Approach :
  - Only keep couplings believed to be important
    - Neglect far-away portions of layout
    - Discard “large” resistors
    - Discard “small” areas
    - Limit type of analysis that can be performed
- Which to use?

Suggests An Obvious Methodology

- Massive coupling problems are not about extraction – can't extract everything and bring in context later.
- Look at impedances controlling strong (possibly indirect) paths
  - Use to place lower bound on global coupling
  - Discard anything that doesn't substantially increase coupling
- Find an efficient way to represent the rest
  - Must work in analysis tools : circuit simulators

Exploiting Multilevel Information

- Multilevel decomposition can be used to further decompose matrix into dominant/secondary interactions
  - Primary Interactions (Keep)



  - Third-Order Interactions (Drop)
  - Second-Order Interactions (Keep. How?)

Global Parasitic Analysis

- Open problem : simulate tightly coupled system, rigorously bound the effect of parasitic couplings.
- Key: context + algorithms. Think methodology & design, not simulation.
- Prediction : by 2012, radiation-aware IC routers.

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  - Global parasitics
  - Managing Abstraction

Design Across Multiple Abstraction Levels

- The old way (for analog/RF design):
  - Decide on some high-level specs, budget between blocks
  - Design the blocks, simulate, layout; repeat till converged
- The new way :
- Modeling is key, right?
- Might as well drag out the model reduction card here too!
- Success for : time-varying linear systems, weakly nonlinear systems

Nonlinear Systems

- Explicit Projection [many references]

$$\frac{dx}{dt} = f(x) + Bu \longrightarrow \frac{dz}{dt} = V^T f(Vz) + \hat{B}u(t)$$

  - All detailed information in $f(\bullet)$ is generally required
  - Almost as expensive as original model ; model complexity unbounded as component number $N \to \infty$
  - Cannot push to higher abstraction levels!!!!

Polynomial Approximations

- Expand nonlinearity in multi-dimensional polynomial series

$$f(x) = A_1 x + A_2 x^{(2)} + A_3 x^{(3)} + \ldots$$

where

$$x^{(1)} \equiv x = \begin{bmatrix} x_1 & x_2 & \ldots & x_n \end{bmatrix}^T \quad x^{(2)} \equiv x \otimes x = \begin{bmatrix} x_1 x_1 & x_1 x_2 & \ldots & x_n x_n \end{bmatrix}^T \text{ etc.}$$

Each term A_q is a q-dimensional tensor, represented as an $n \times n^q$ matrix

- Differential equation becomes

$$\frac{dx}{dt} = A_1 x^{(1)} + A_2 x^{(2)} + A_3 x^{(3)} + \ldots + Bu$$

- To match first few terms in functional series expansion, only need first few polynomial terms

Projection of polynomial terms

- Draw x from reduced space as $x = Vz$
- Identity for Kronecker products

$$(x \otimes x) = (Vz \otimes Vz) = (V \otimes V)(z \otimes z)$$

- Project tensors

$$A_{(2)}(x \otimes x) = A_{(2)}(Vz \otimes Vz) = A_{(2)}(V \otimes V)(z \otimes z)$$

- Gives reduced model

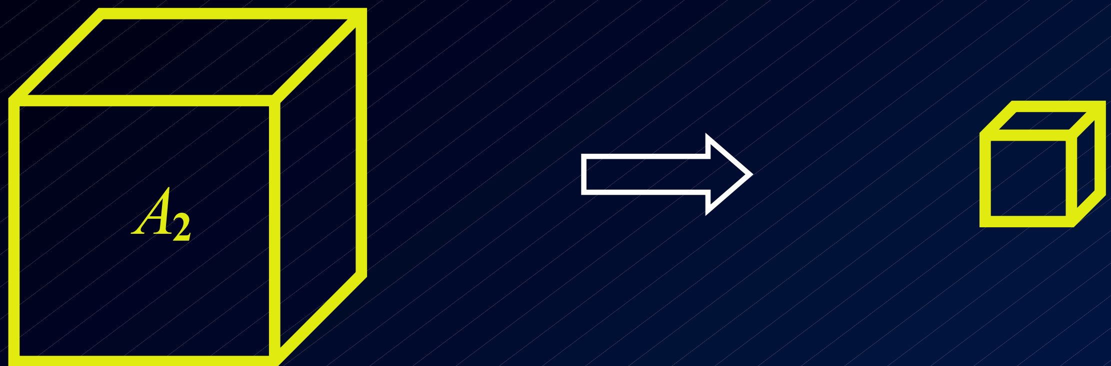
$$\frac{dz}{dt} = \hat{A}_{(1)}\, z^{(1)} + \hat{A}_{(2)}\, z^{(2)} + \hat{A}_{(3)}\, z^{(3)} + \ldots + Bu$$

$$\hat{A}_{(1)} = V^T A_{(1)} V, \qquad \hat{A}_{(2)} = V^T A_{(2)}(V \otimes V),$$

$$\hat{A}_{(3)} = V^T A_{(3)}(V \otimes V \otimes V),$$

etc.

Reduced polynomial models



- Projection procedure produces reduced model in same polynomial form $\hat{A}_{(2)} = V^T A_{(2)}(V \otimes V),$
  - key tensor components are compressed to lower dimensionality
  - procedure is generally known
  - Kronecker forms provide convenient general notation

Computing Projection Spaces

$$\frac{dx}{dt} = f(x) + Bu \longrightarrow \frac{dz}{dt} = V^T f(Vz) + \hat{B}\,u(t)$$

- How to get V ?
  - Analysis of linearized models [Ma88] -- Popular, Often Works
  - Sampling of time-simulation data [Sirovich87] -- Expensive
  - Nonlinear balancing [Scherpen93] -- Not Computable
- No guarantees on system approximation properties, no a-priori way to tell when methods work or fail
- Variational Analysis Procedure : Extends Projection/Rational Interpolation Connection to Polynomial Systems

Problems with Polynomial Models

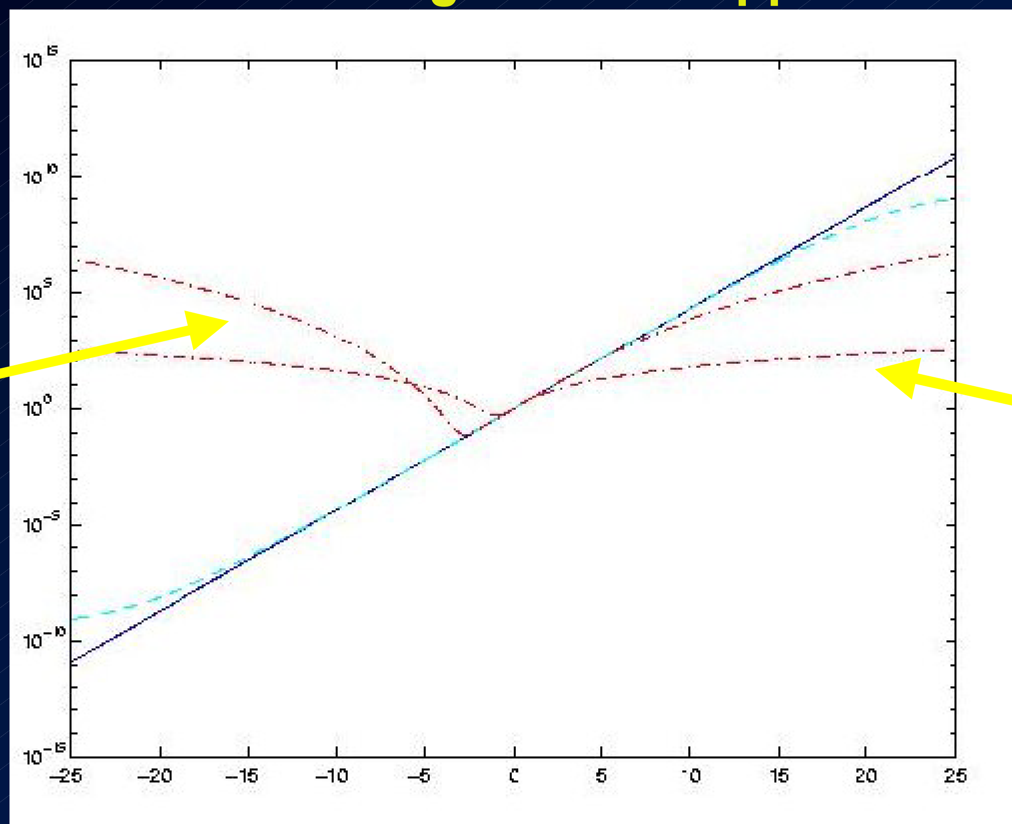
- Model size grows exponentially with order of nonlinearity
  - potentially large models
  - intrinsic in polynomial descriptions (e.g. Volterra series)
  - practical for simple *system* nonlinearities needing only few terms in functional series (cubic at most)
- Reduced models often unstable for large inputs
  - believed to be an artifact due to breakdown of polynomial approximations
  - probably hopeless to get a well-behaved reduced model if the truncated polynomial model is not well-behaved

Polynomials Approximate Only Locally

$$I = I_s(e^{v/vt} - 1)$$

Consider second and eighth order approximates

energy generating



inaccurate

Design Across Multiple Abstraction Levels

- Open problem :
  - Robustness guarantees for time-varying, weakly nonlinear systems
  - Strongly nonlinear (anything)

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- Synthesis Focus
  - Parameter Variation
  - Exploration & Optimization

Parametric Models

- Why :
  - Design in the presence of variations, i.e. analysis for manufacturability
  - Models in an automated design context (synthesis)
- Embed variation in model itself

$$sx = A(p)x + Bu \qquad y = Cx + Du$$

- Open problem : large # of parameters

Emerging Methodologies

- Platforms, synthesis, re-targeting, re-use
- Automated search, characterization, model generation
- Prediction : Biggest driver for automation, simulations in parallel (*not* parallel simulation)

Summary

- Still a future for numerics people? Yes!
- Highest likelihood of impact
  - Esoterica (ultra-high frequencies, RF, optical). New ways to analyze tough problems.
  - Tight coupling with design methodology, physical design, or IP creation tools.
- Some open problems:
  - Unstructured multiple timescale problems,
  - Large-scale parasitic analysis
  - Modeling of distributed, nonlinear, parameter-varying systems