# Automated Macromodel Generation for (Electronic) Systems

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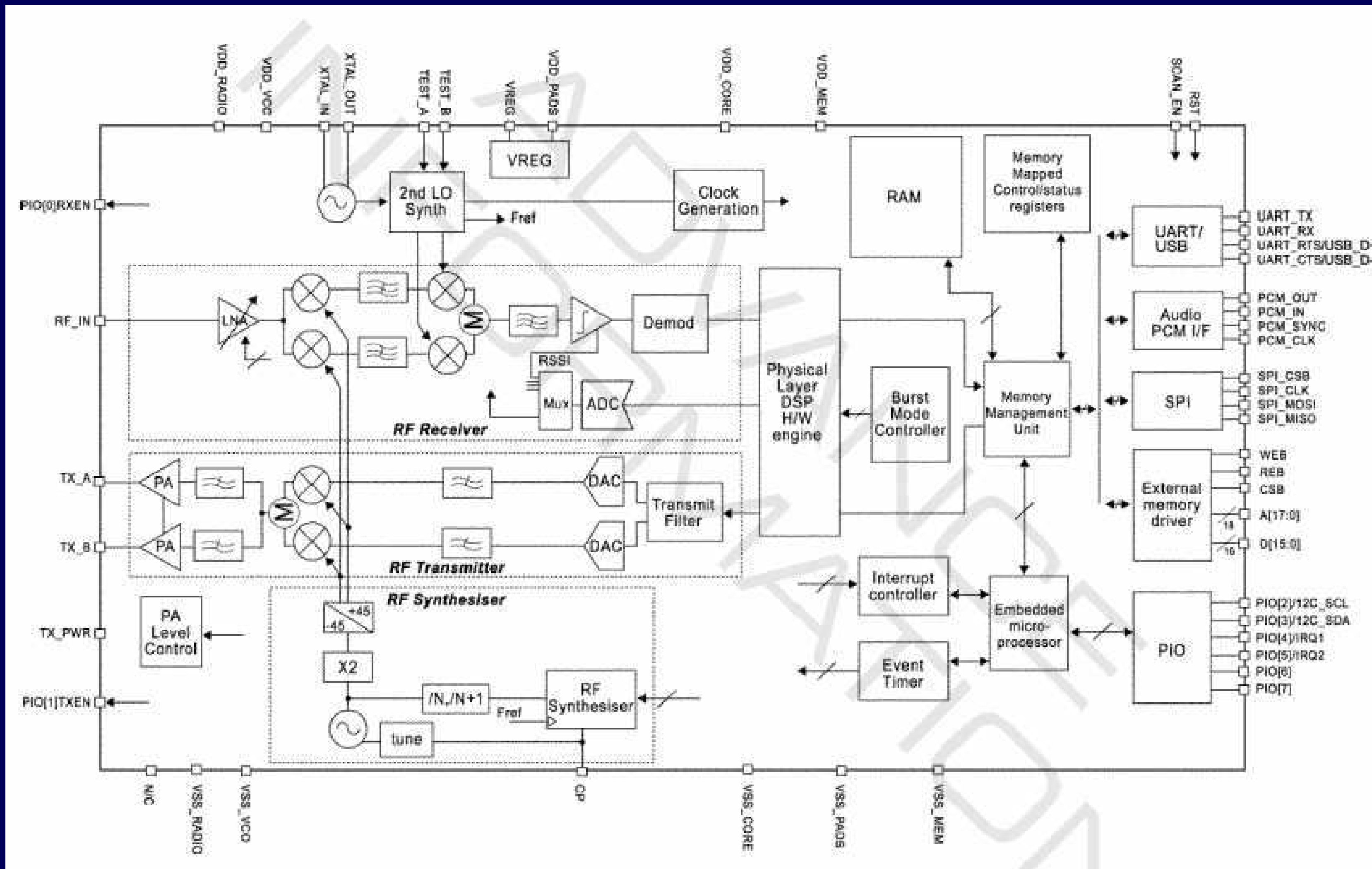
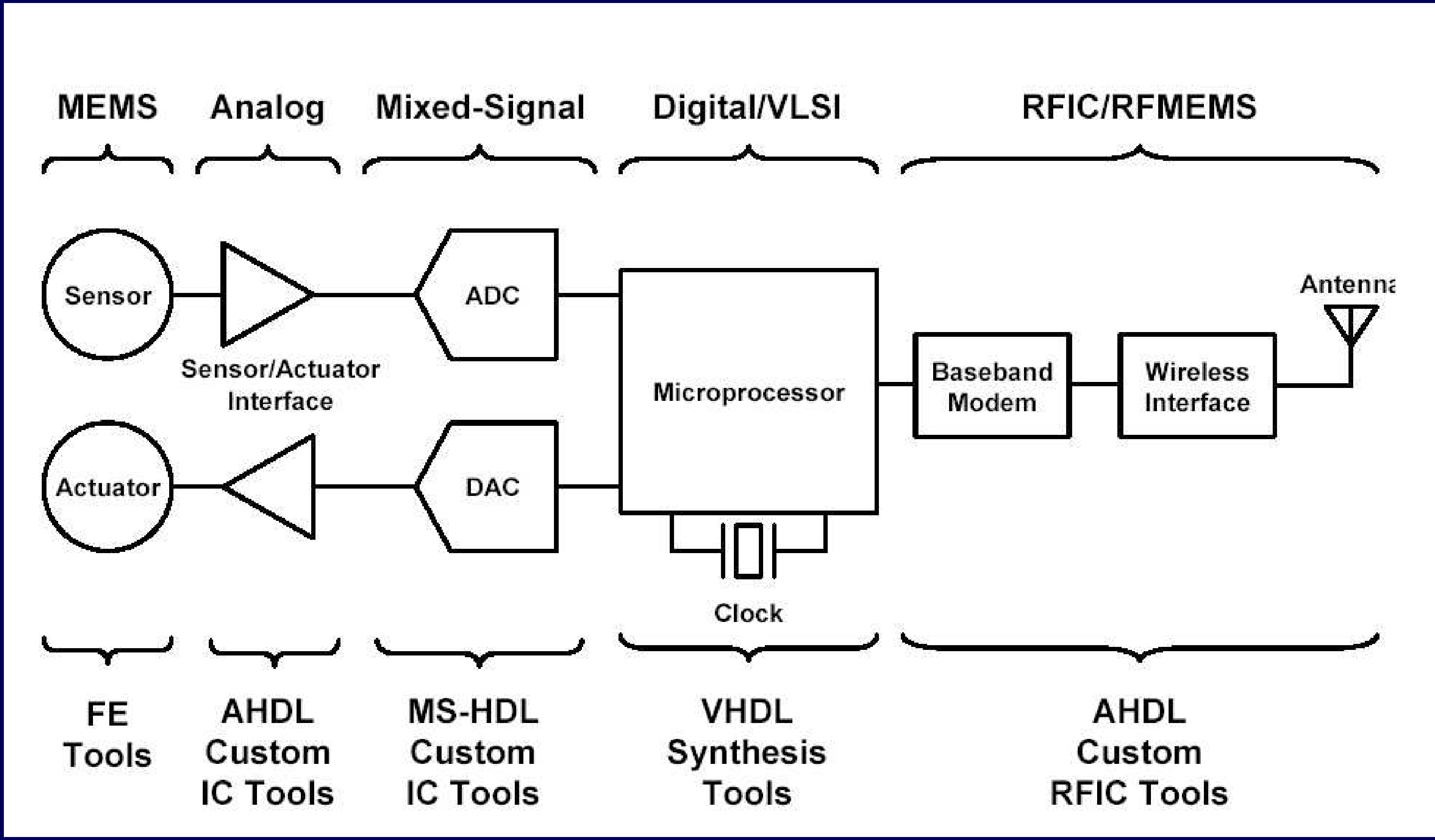
# Bluetooth mixed-signal RFIC



Cambridge Silicon

☛Cheap ☛Low margins☛ **Must work first time**

# MEMS Sensor System



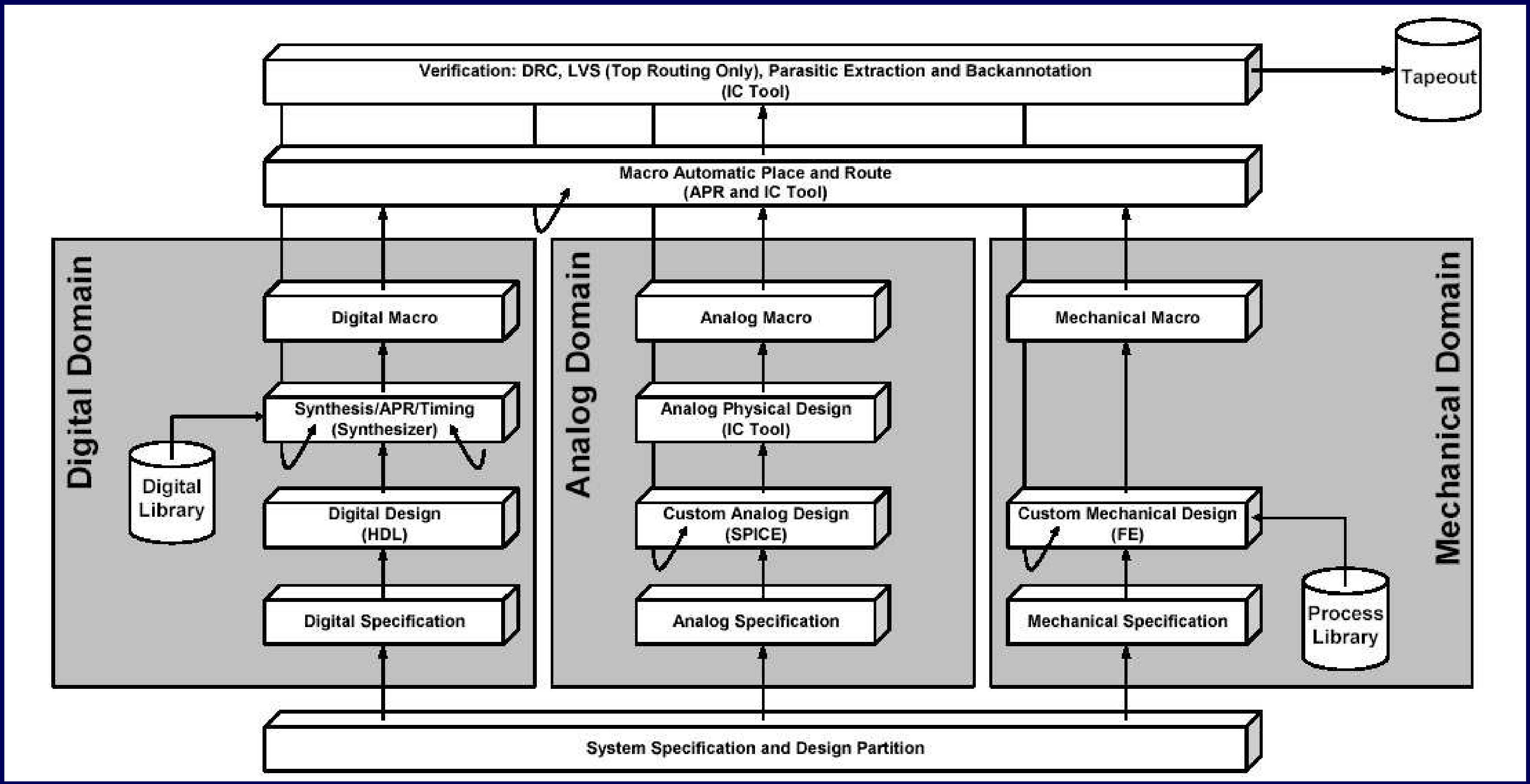

McCorquodale et al, U of Michigan

☛Multiple physical domains to model

# Verification Challenges

- Large entire (multi-physics) systems to verify
- Interactions between blocks, “second-order effects”
- Interconnect, coupling, noise
- Speed with SPICE-like accuracy becoming necessity
- **Impossible at SPICE level**

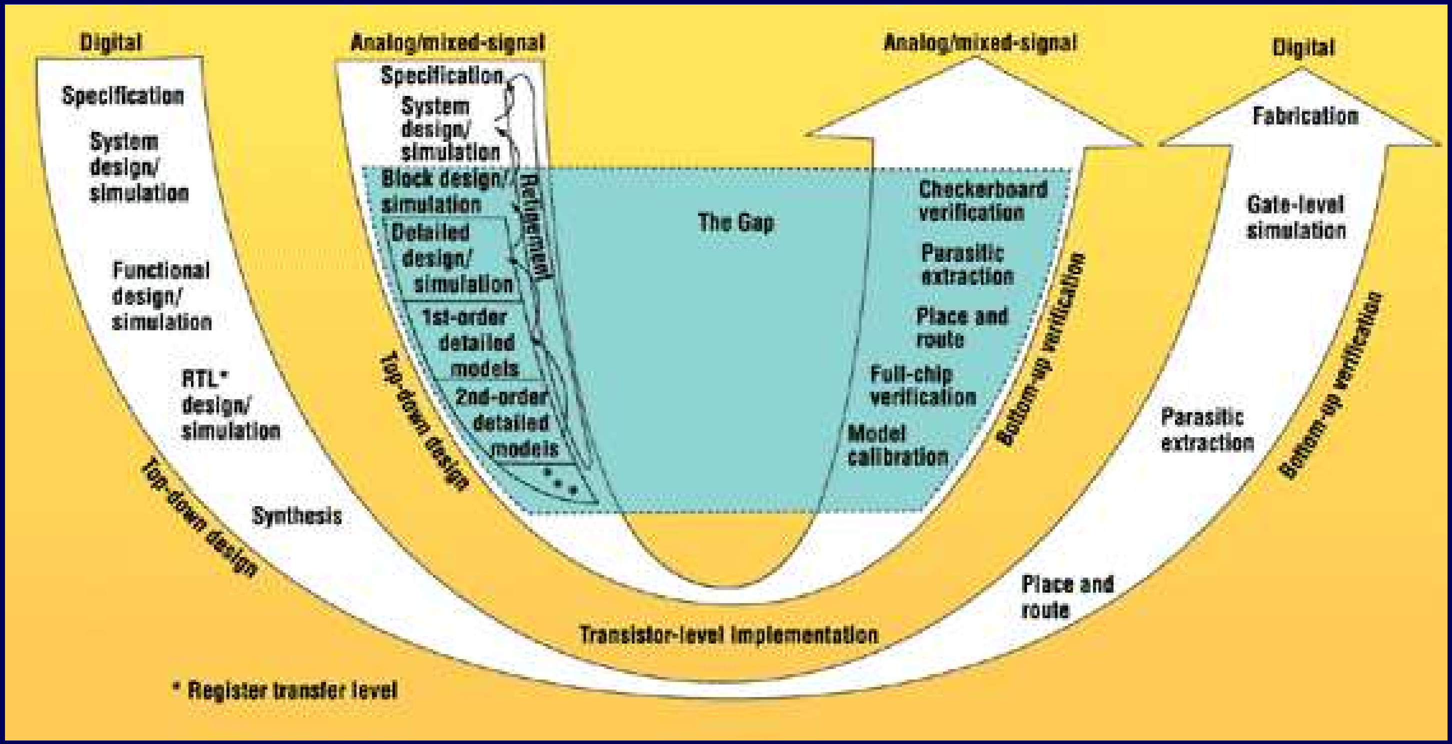
# Today's bottom-up design




McCorquodale et al, U of Michigan

☛3-5 spins = cutting edge; >10 at Lucent

# “The Gap”




EE Times

“The primary problem hindering the change to analog top-down design and bottom-up verification has been the **lack of tool support for the design process between system-level specification and transistor-level implementation**, as well as between transistor implementation and chip fabrication. These missing tools are commonly referred to as The Gap." - EE Times, 2001

# “The Gap”

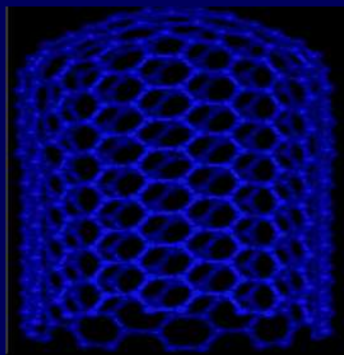
☛Solution: **good bottom-up macromodels**

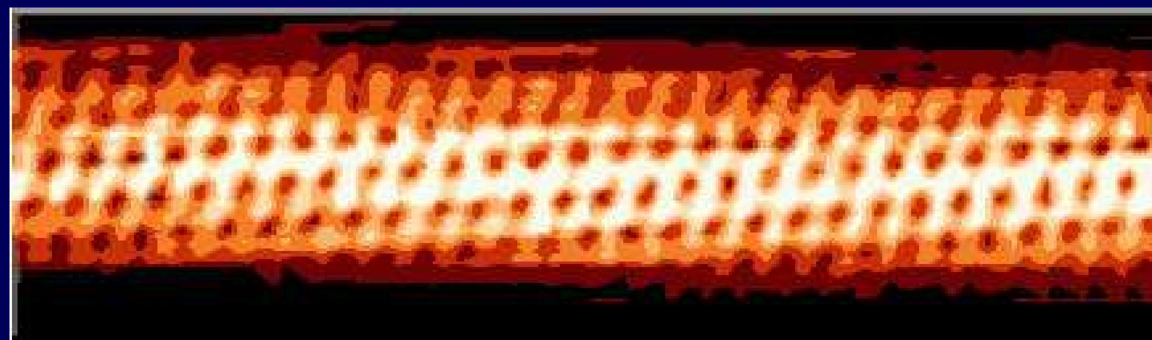
# Generating Macromodels

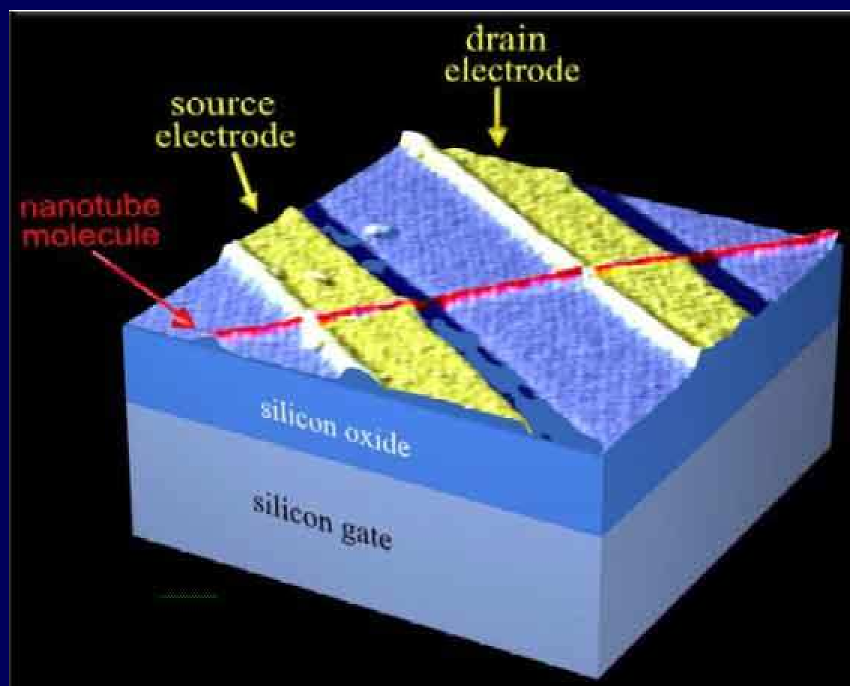
- Today: **<u>manually</u>**
- Highly skilled activity
  - what if designer leaves?
- Mistakes (esp “second-order”)
- Time-consuming
- Tomorrow: myriad new technologies
  - Carbon nanotubes, spintronics, ballistic nanotransistors, photonic crystals, ...

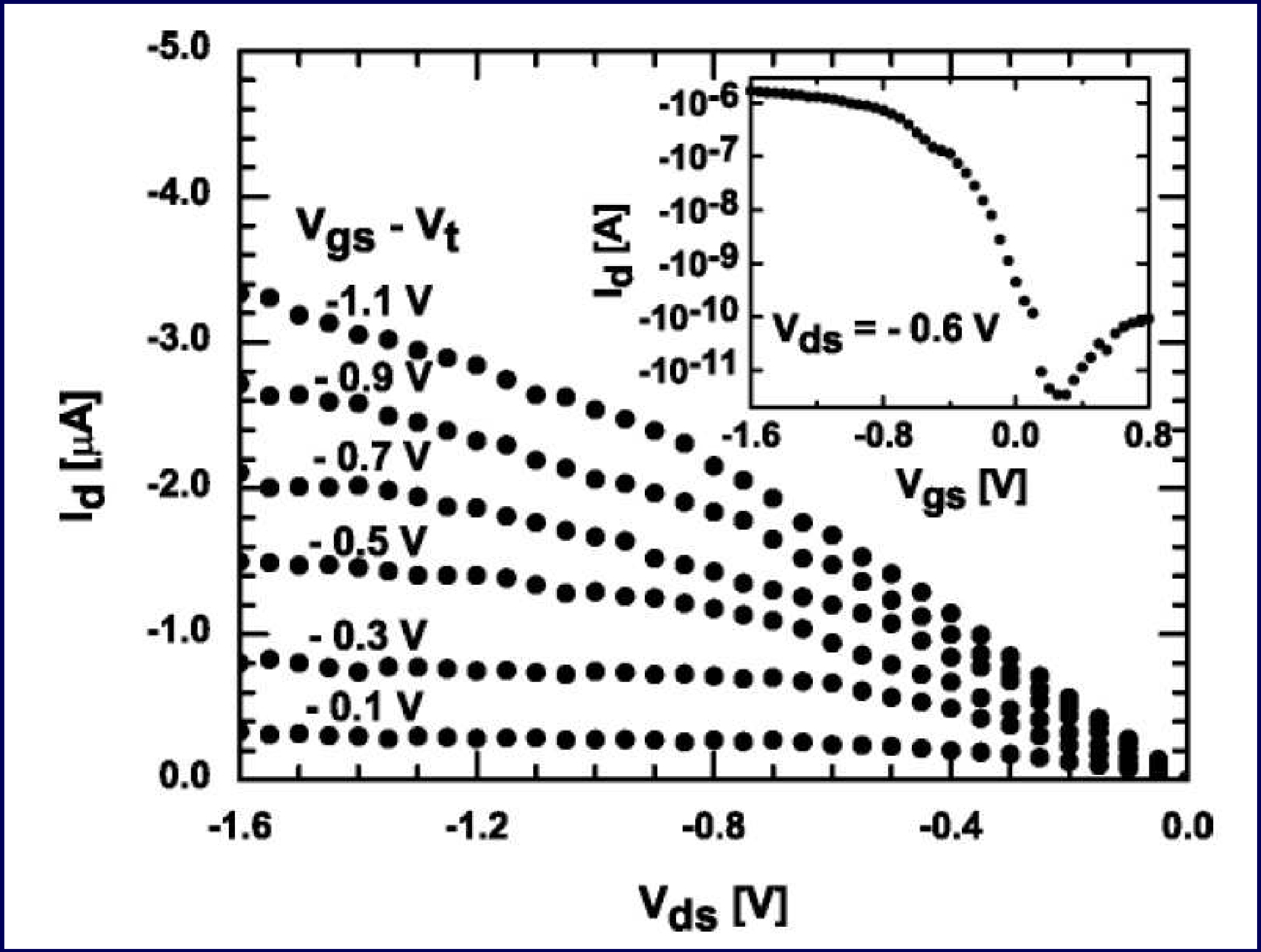
# Carbon Nanotubes





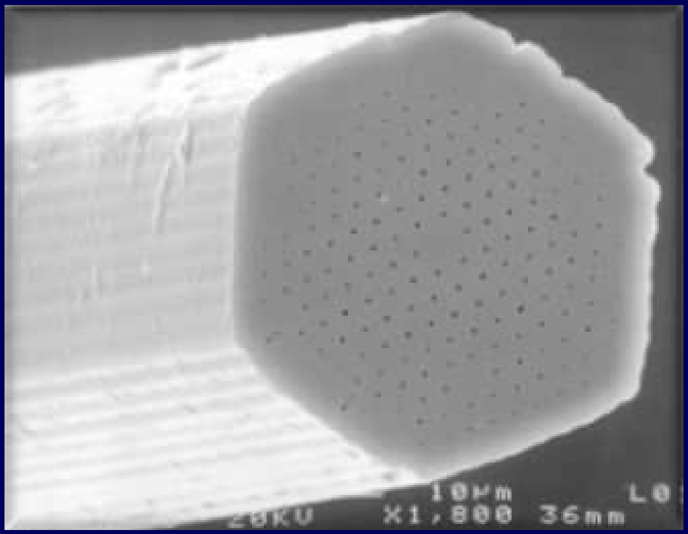


# Carbon Nanotube FETs

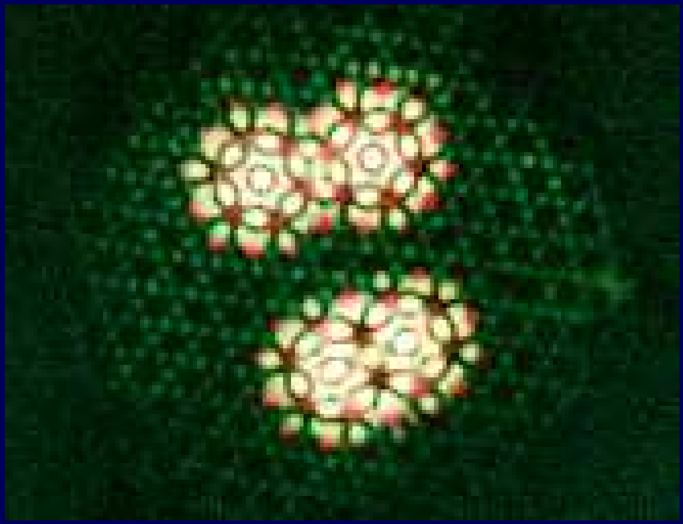



☛Poor device characteristics: **manual abstraction hard**

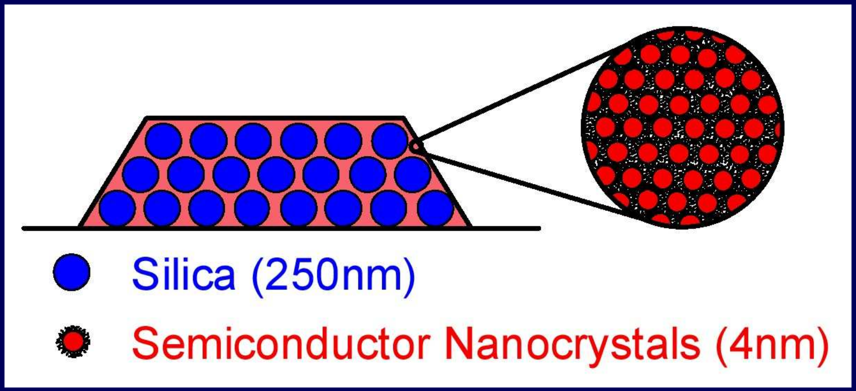
# Photonic Nanocrystals



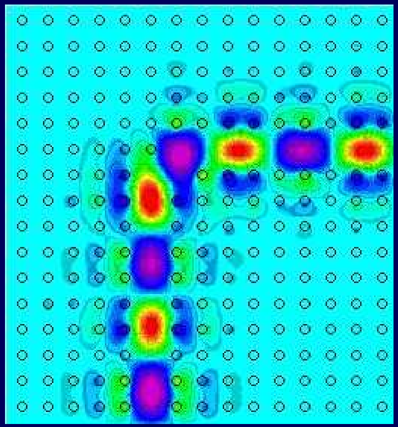

Blaze Photonics



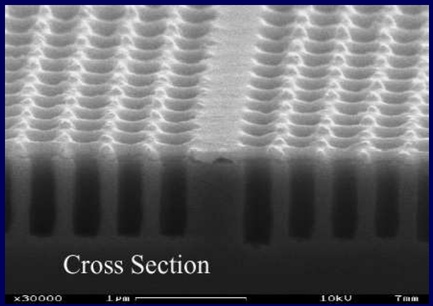
Blaze Photonics




NEC



MIT

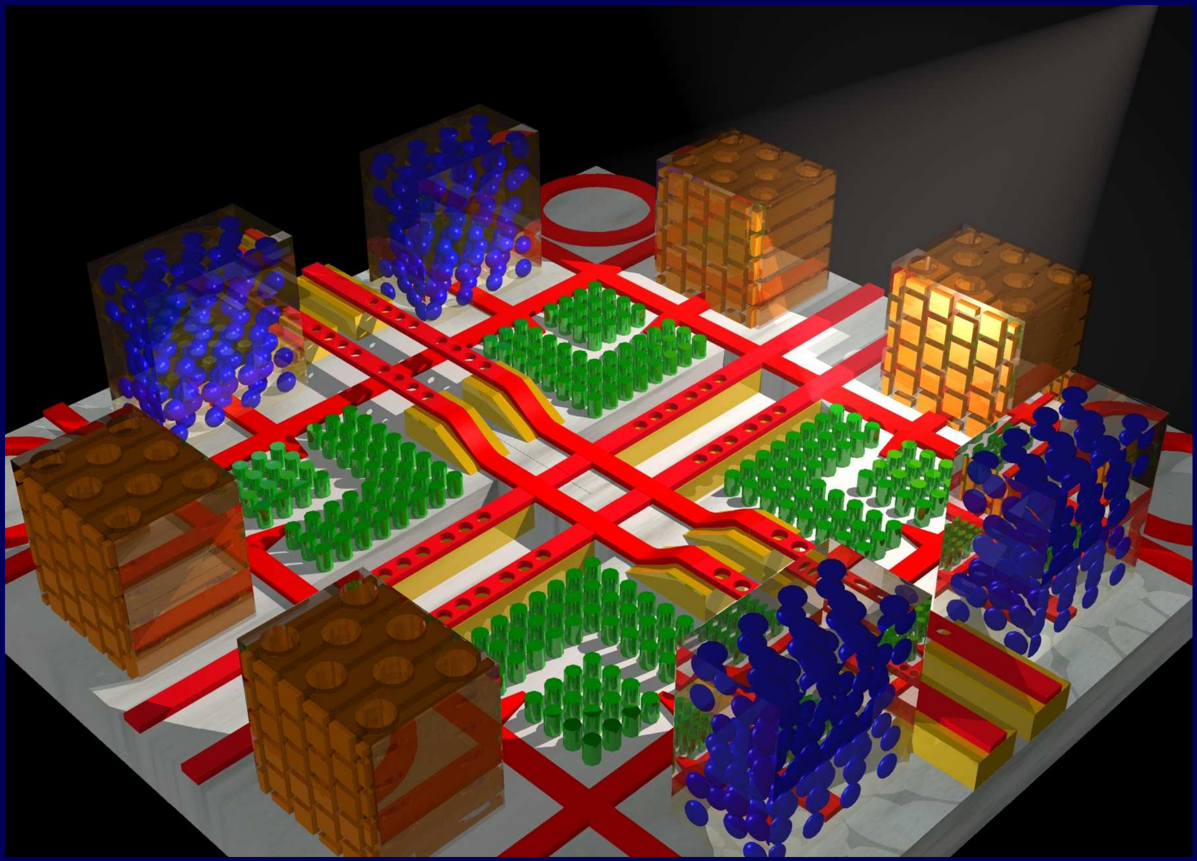



Pallab Bhattacharjee, U Mich

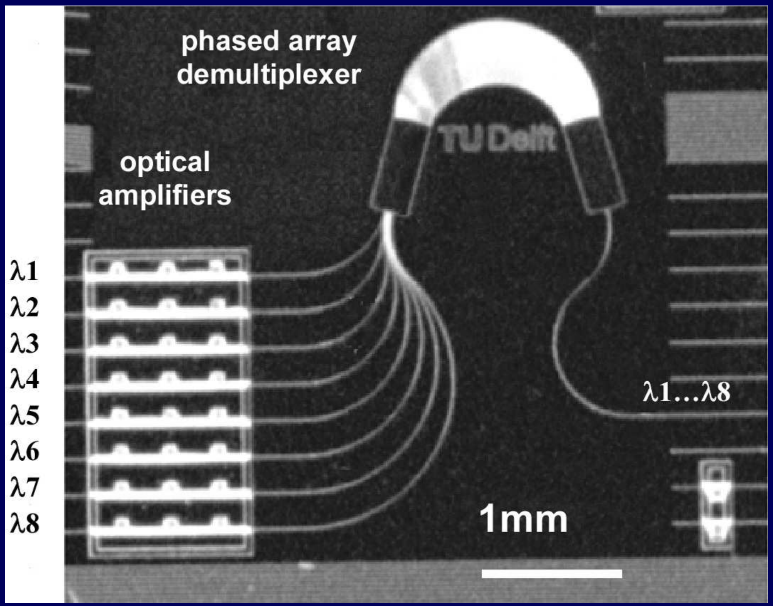
# Photonic Crystal Applications

- Optical interconnect, nano-lasers, electro-optic modulators, freq multipliers...

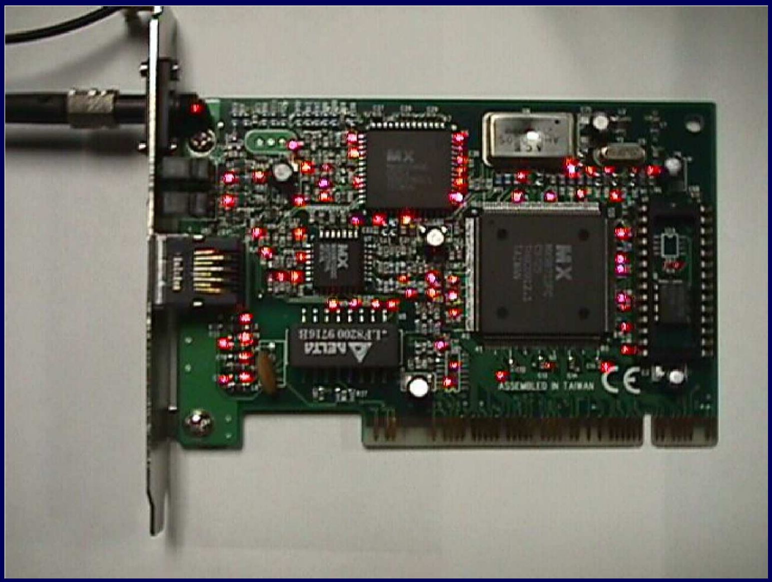


Joannopoulos group, MIT

# Integrated Opto-electronics



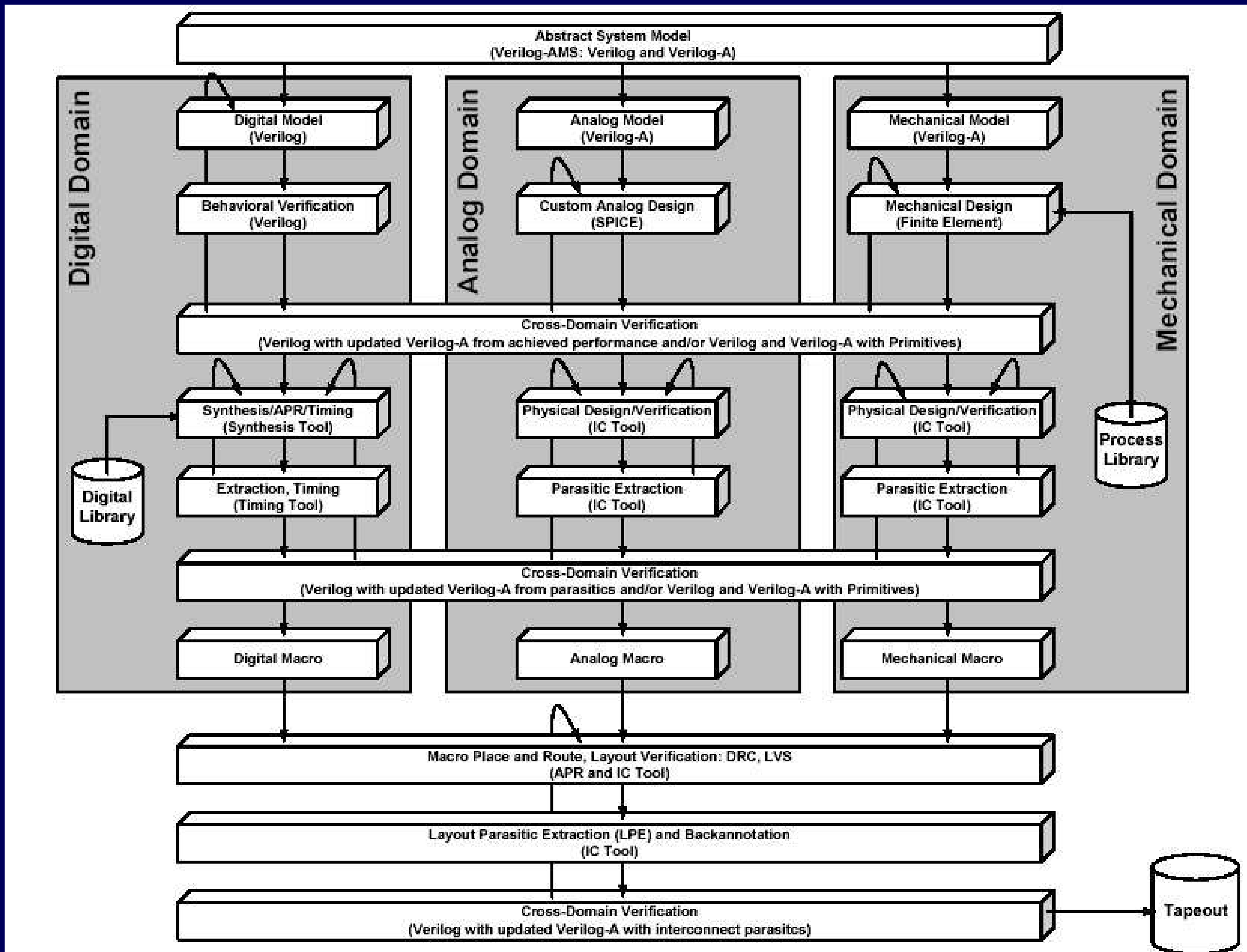
TU Delft


Ray Chen, UT Austin

- More domains to macromodel at system level

☛Manual expertise scarce: **general automated capability**?

# Top-down Design




McCorquodale et al, U of Michigan

# Automated Macromodelling

- The dream: **push-button bottom-up model generation**
  - prescribed accuracy guaranteed
  - trade-off speed vs accuracy
- **Needed** for design sustainability
  - complexity exceeds manual ability to keep up

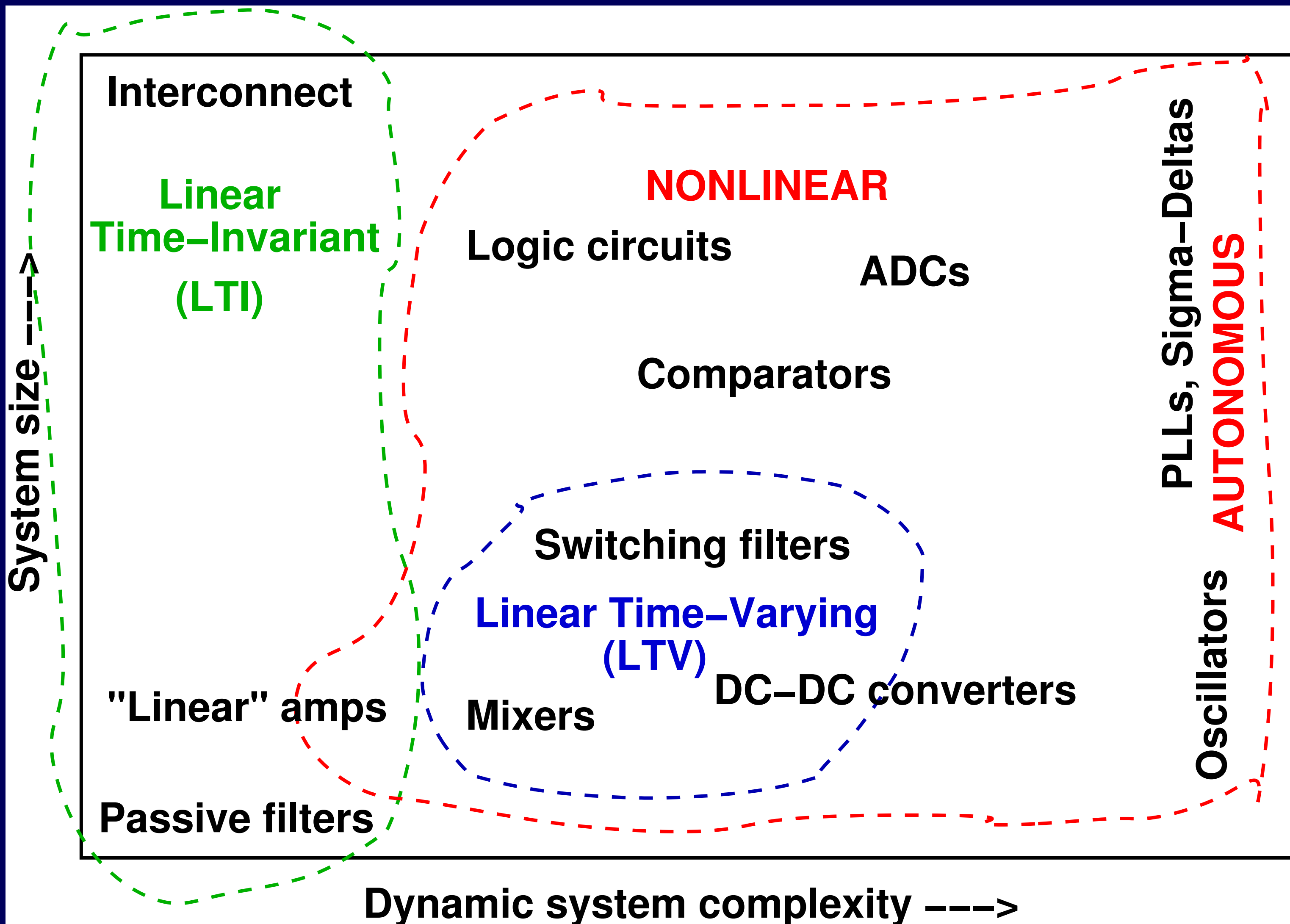
# The Difficulty

"At this point, you may wonder why you should bother with behavioral libraries and calibration. Why not just **submit the transistor-level design to some smart software and let it come up with a model**? Unfortunately, despite some claims to the contrary, **practical model synthesis is still a long way off**. Attempts at this technology rely on **pre-existing templates, which are unlikely to exist for leading-edge or proprietary designs**. There's **no pushbutton approach to analog modeling**, and from all indications, **this will remain the case for some time to come**." - EE Times, 2001

- Perhaps not quite so bleak!
- Automated macromodel generation **is** difficult

# Why Difficult?

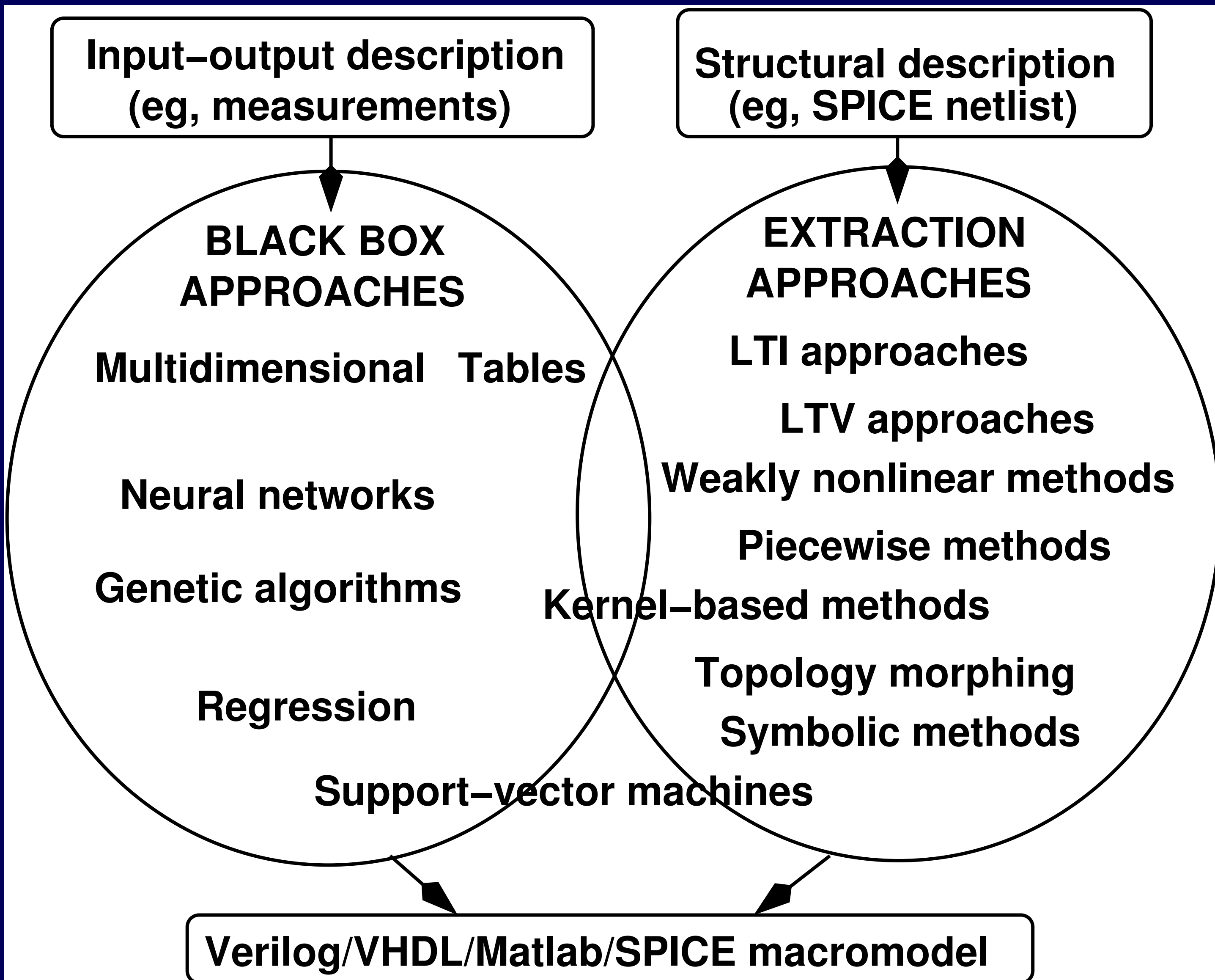


# Approaches to Macromodelling

- **Black-box** problems
  - samples of input-output pairs
  - measurement and/or simulation
  - **paucity of information**
- **Extraction (bottom-up reduction)** problems
  - Detailed circuit/system info available
  - eg, SPICE netlist: **differential equations**
  - **surfeit of information**
  - **potential for better macromodels**

# Automated MM Approaches

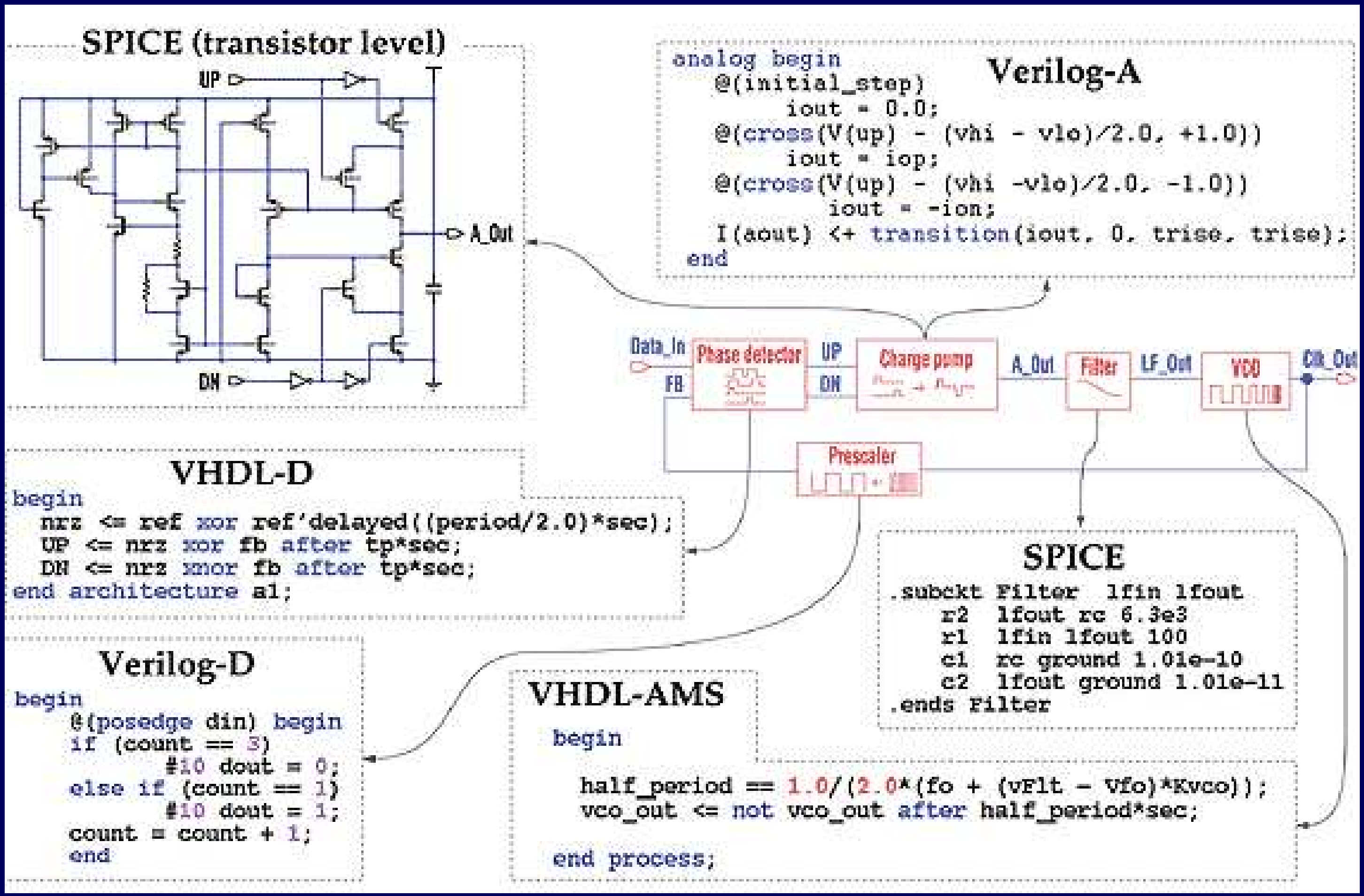


# Macromodelling Languages

- Output of macromodelling process
- AHDL Languages - eg, Verilog-A, VHDL-AMS
  - the EDA choice
- Matlab/Simulink
  - widely used by designers
- SPICE(?)
- **Fundamentally**: (integro-)differential-algebraic equations

# Macromodelling Languages




EE Times

☛Multiplicity of languages, should inter-operate

# "Algorithmic" MM Approaches

- Mathematical algorithms based on theory
- Provably preserve some useful property
  - eg, moments of transfer function
- **AWE:** first prominent method (LTI)
- PVL, PRIMA, TBR methods (all LTI)
- Variety of nonlinear, LTV methods
- **Generally applicable** (eg, multi-physics)

# Linear Time Invariant Systems

- What is LTI?
  - Scale input waveform $\Rightarrow$ scale output waveform
  - Time-shift input $\Rightarrow$ time-shift output
- **Interconnect**, "linear" circuit elements
- Well understood: 50 years of theory
  - Laplace transforms, LTI ODEs, controllability/observability, ...
  - Powers hand analysis by most designers

# Asymptotic Waveform Evaluation

- AWE (Pillage/Rohrer ~1990)
- **Preserve moments** of LTI **transfer function**
  - frequency-domain xfer-fn derivatives
  - time-domain rise/fall time interpretations
- **Explicit moment matching**
  - calculate moments of original system
  - solve (linear matrix) equations to get small rational-function macromodel

# LTI MM Accuracy/Scalability

- Increasing size does not increase accuracy
  - Explicit moment generation, Hankel-matrix-based calculation numerically ill-conditioned
- **Implicit moment matching**: Krylov-subspace methods
  - don't calculate moments: generate related Krylov subspaces robustly (Lanczos/Arnoldi methods)
  - generate macromodels directly - moments matched implicitly
- Pade-via-Lanczos **(PVL**, Feldmann/Freund ~1994/5)

# LTI MM Generation

$u(t)$

**Original Linear Space**

$$E\frac{dx}{dt} = Ax + Bu(t)$$

$y = Cx$

$$H(s) = C(sE - A)^{-1}B$$

$$x = Vz, x \in \mathbf{R^n}, \mathbf{z} \in \mathbf{R^q}$$

$$\hat{H}(s) = \hat{C}(s\hat{E} - \hat{A})^{-1}\hat{B}$$

$u(t)$

**Reduced Linear Space**

$$\hat{E}\frac{dz}{dt} = \hat{A}z + \hat{B}u(t)$$

$y = \hat{C}z$

# LTI MM Stability/Passivity

- Interconnect: basically R, L, C elements
  - **Passive**: can't generate energy
- But macromodels can!
  - small inaccuracies in MM parameters $\Rightarrow$ qualitative stability problems $\Rightarrow$ useless MM!
  - must preserve passivity
- Passivity for RC, RLC circuits
  - Congruence transformations (Kerns/Yang 95)
  - PRIMA (Odabasioglu/Celik/Pileggi, 97)
  - Others: PVL extensions, beyond RLC ...

# LTI MM Optimality/Compactness

- Truncated Balanced Realizations (TBR)
  - Silveira/White et al
  - Trim internal states that are not **controllable/observable**
  - Provably optimal: minimizes I/O norm error for given MM size
- But: computationally expensive
  - cubic in original size
- Mix and match: Krylov + TBR (Phillips et al 02)
  - First create big (~100s) MM via Krylov
  - Use TBR to make compact MM

# LTI MM Summary

- Important features
  - Accuracy vs size tradeoff
  - MM scalability
  - MM passivity
- Computational properties
  - AWE, Krylov methods linear with original size
  - TBR methods cubic (but **new results from Joel**!)
- Relatively mature and practically usable
- Basis for nonlinear approaches

# Nonlinear Macromodelling

$u(t)$

**Original Nonlinear Space**

$$E\frac{dx}{dt} = f(x) + Bu(t)$$

$y = Cx$

$$H(s) = ?$$

$$x = V(?)z$$

$$\hat{H}(s) = ?$$

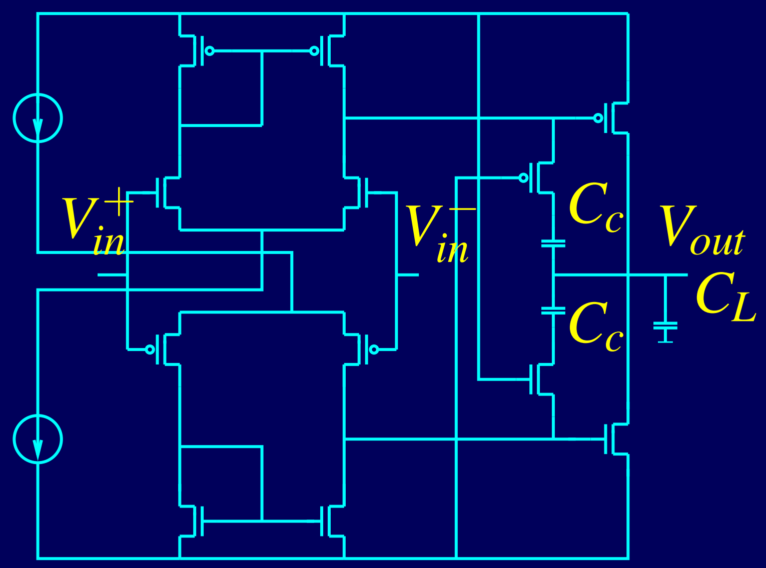
$u(t)$

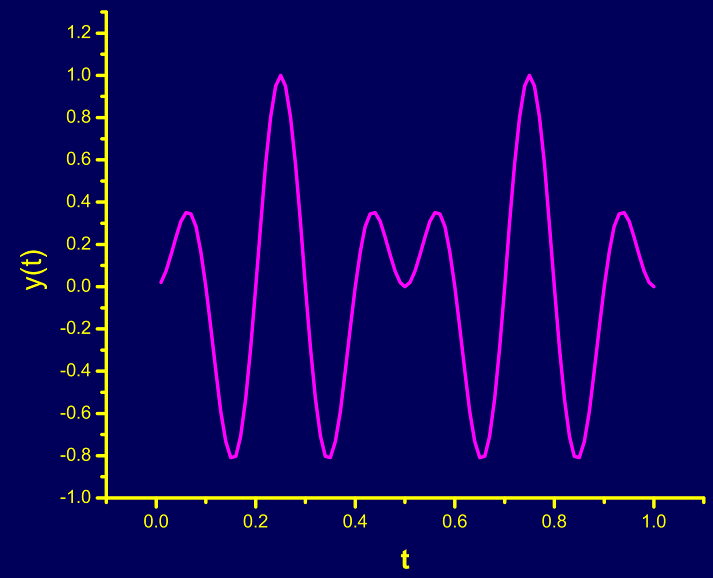
**Reduced Nonlinear Space**

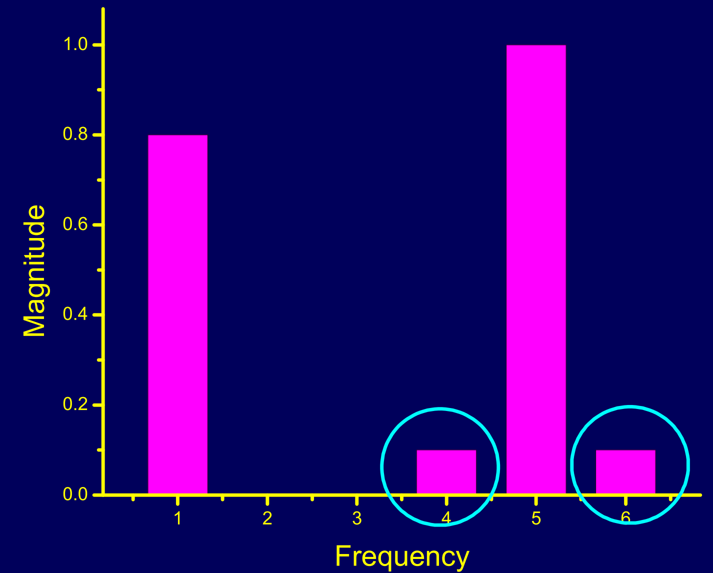
$$\hat{E}\frac{dz}{dt} = \hat{f}(z) + \hat{B}u(t)$$

$y = \hat{C}z$

# Weakly Nonlinear Systems



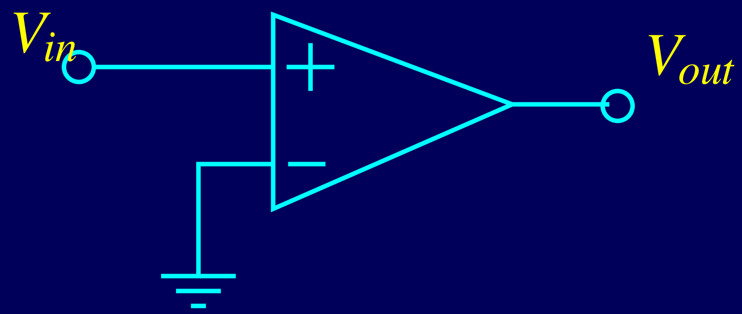



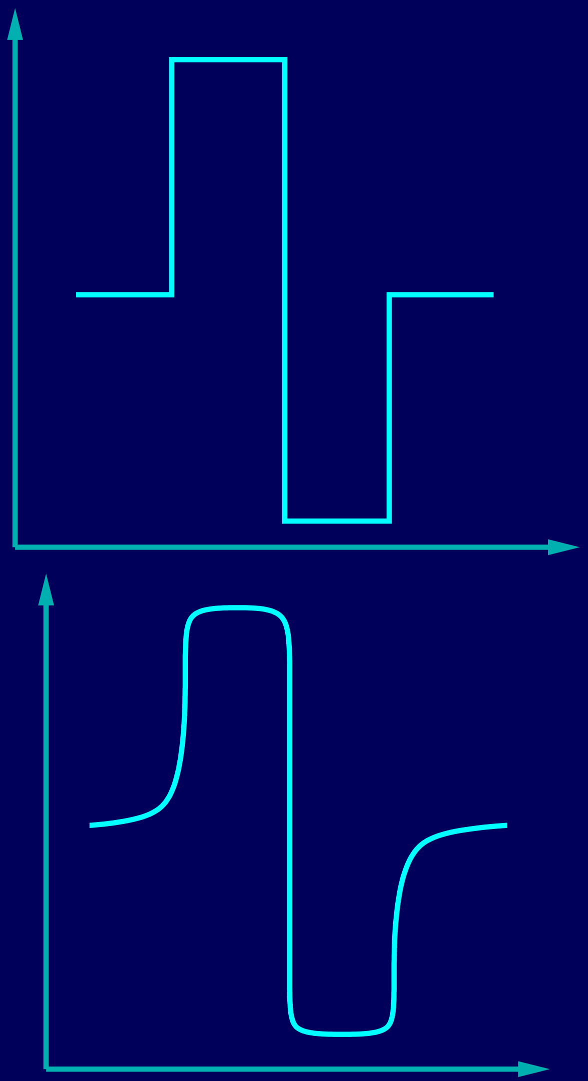

- Distortion, IM important!
- Must capture small distortion/IM

# Strong Nonlinearities

Comparators, switching mixers

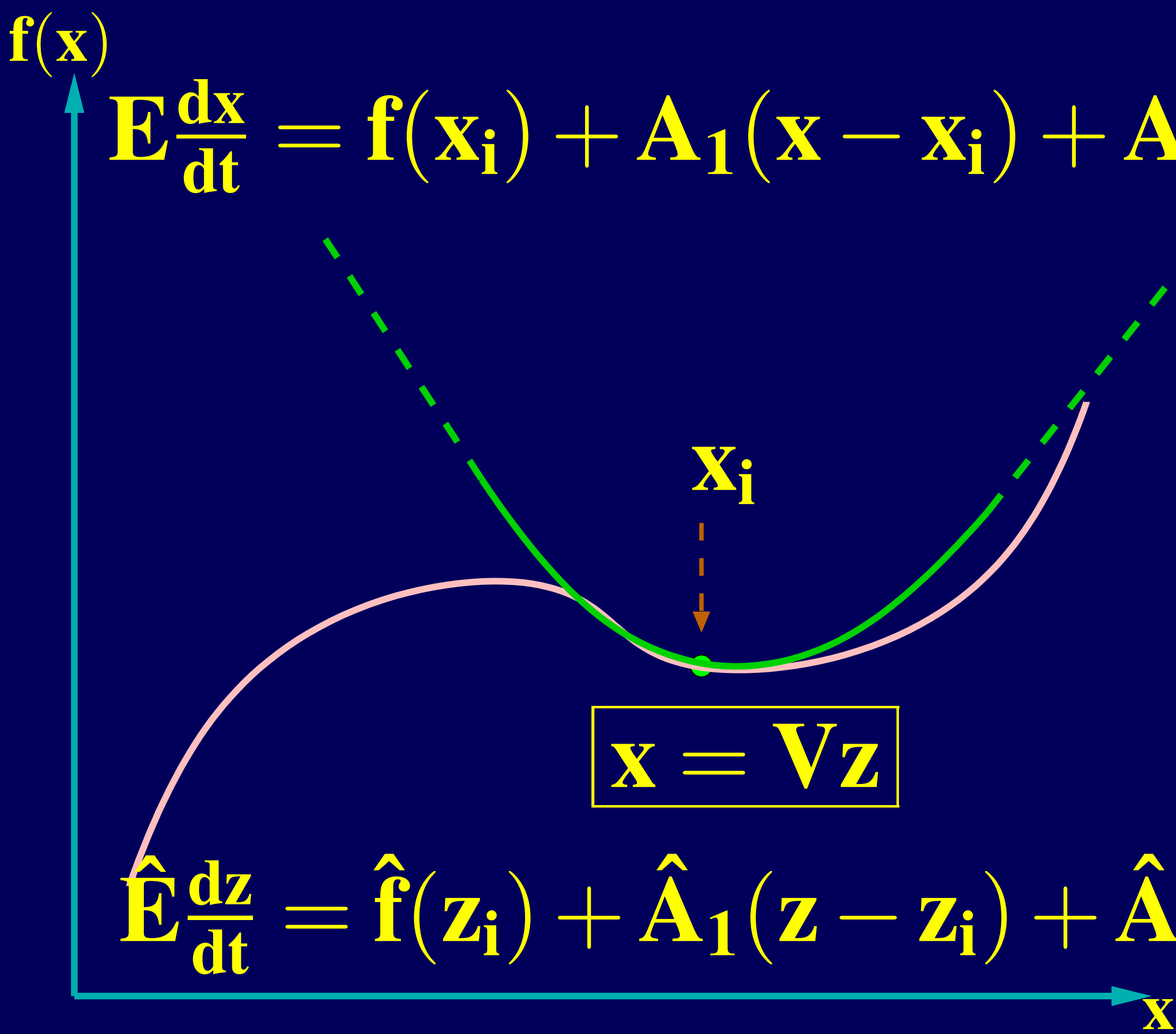



- Large signal clipping
- Must capture strong nonlinearities



# Polynomial Reduction

$$\mathbf{E}\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x_i}) + \mathbf{A_1}(\mathbf{x}-\mathbf{x_i}) + \mathbf{A_2}(\mathbf{x}-\mathbf{x_i})^2 + \mathbf{B}u(t)$$

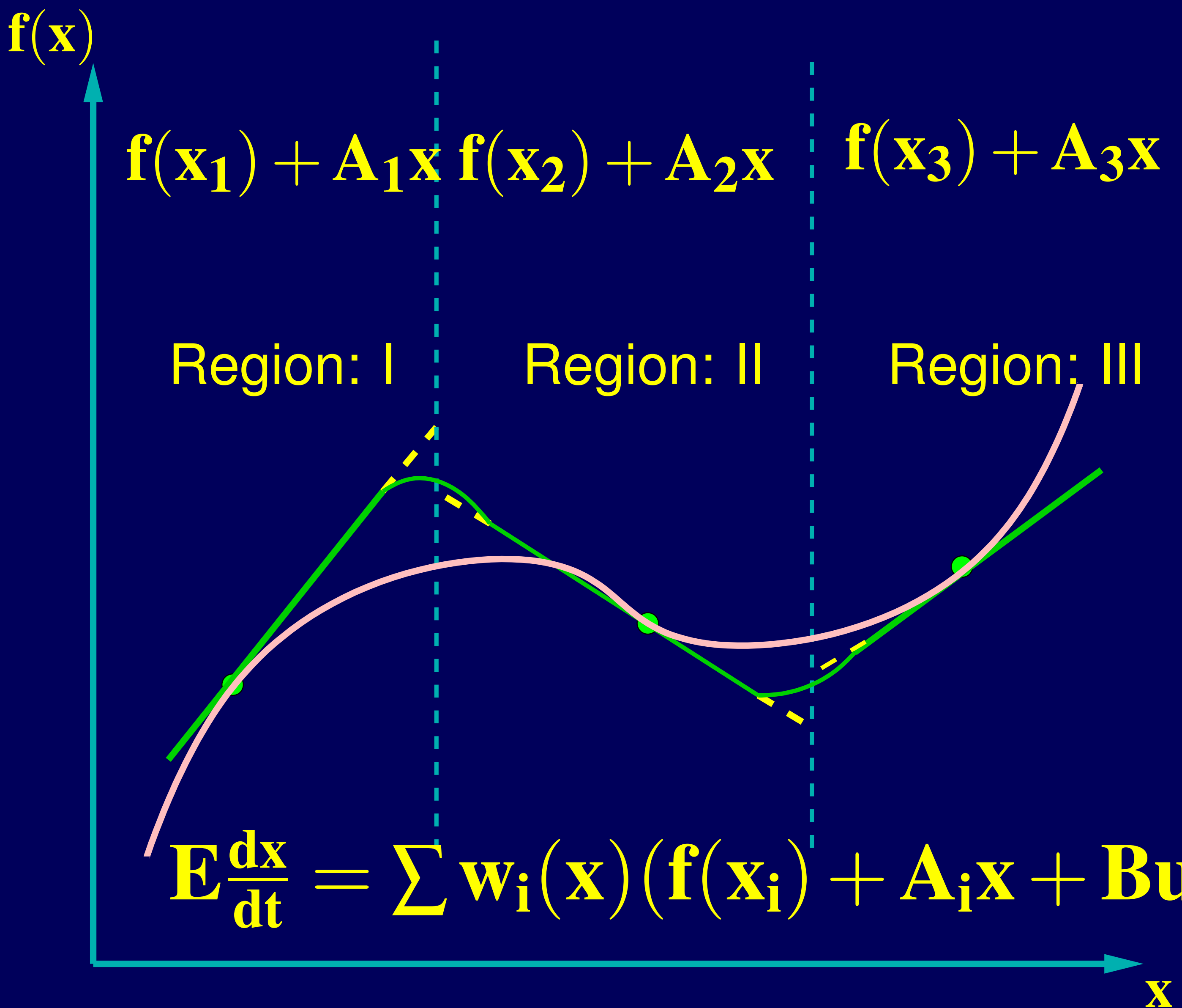



$$\boxed{\mathbf{x} = \mathbf{V}\mathbf{z}}$$

$$\hat{\mathbf{E}}\frac{d\mathbf{z}}{dt} = \hat{\mathbf{f}}(\mathbf{z_i}) + \hat{\mathbf{A}}_1(\mathbf{z}-\mathbf{z_i}) + \hat{\mathbf{A}}_2(\mathbf{z}-\mathbf{z_i})^2 + \hat{\mathbf{B}}u(t)$$

- **Good for small distortion, Poor for large swing**

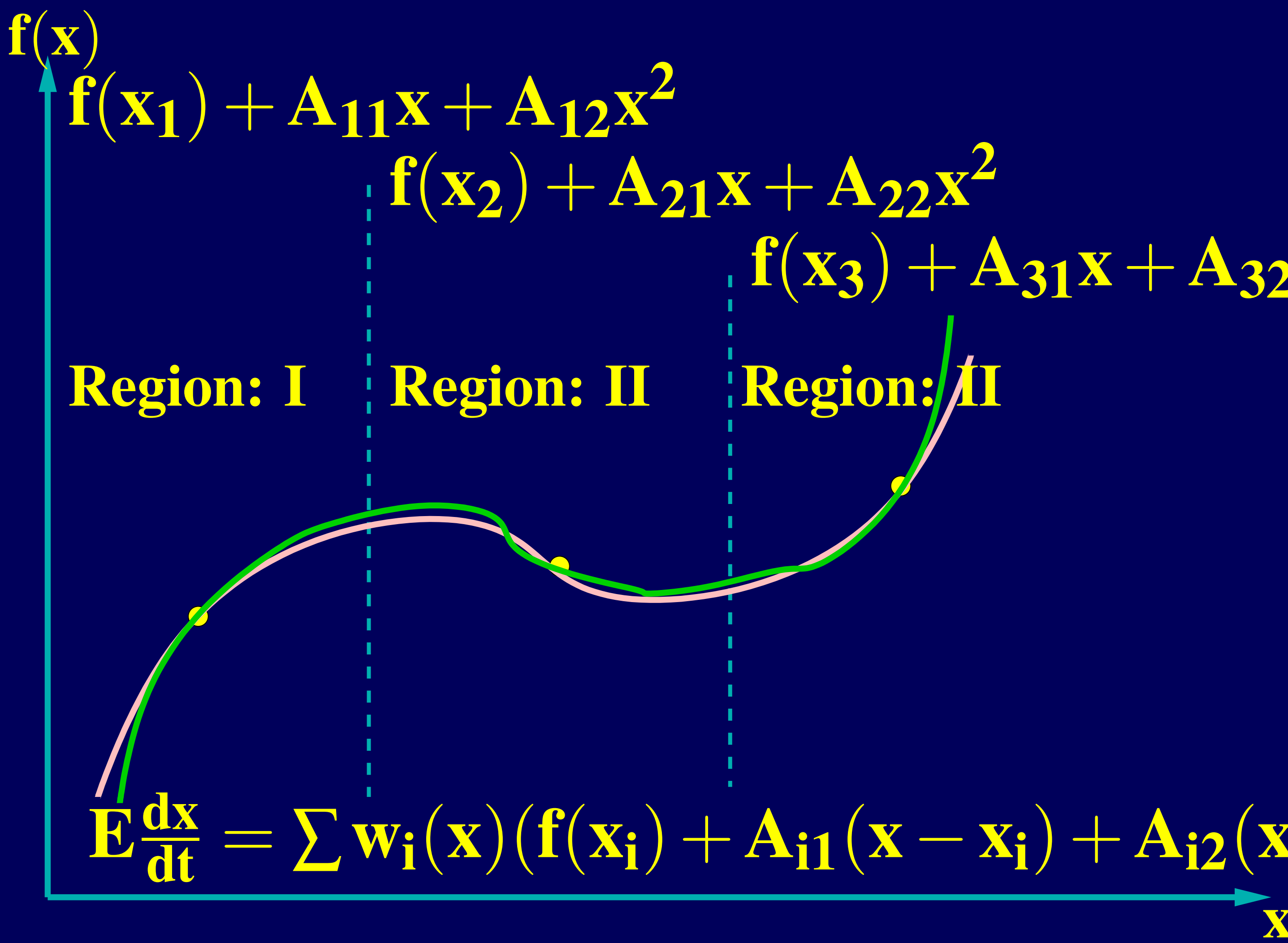
# Piecewise Linear MM




$$\mathbf{E\frac{dx}{dt} = \sum w_i(x)\left(f(x_i) + A_i x + Bu(t)\right)}$$

# Piecewise Poly MM




$$f(x_1) + A_{11}x + A_{12}x^2$$

$$f(x_2) + A_{21}x + A_{22}x^2$$

$$f(x_3) + A_{31}x + A_{32}x^2$$

$$E\frac{dx}{dt} = \sum w_i(x)\left(f(x_i) + A_{i1}(x - x_i) + A_{i2}(x - x_i)^2 + Bu(t)\right)$$

- **Good for small distortion, also good for large swing**

# Nonlinear MM Results

Transient simulation of $1s$, measured on Linux/Matlab

| Transmission Line (27 regions): $u(t) = 2sin(2\pi t) + sin(10\pi t)$ | | | |
|---|---|---|---|
| Model Type | Model Size | Gen. Time [s] | Runtime [s] |
| Full | 100 | — | 8.44 |
| Reduced PWL | 10 | 1.95 | 7.31 |
| Reduced PWP | 10 | 20.1 | 10.91 |
| Cascade Amplifier (17 regions): $u(t) = 3 + 10^{-3}(sin(4\pi t) + sin(10\pi t))$ | | | |
| Full | 50 | — | 29.7 |
| Reduced PWL | 10 | 10 | 7.35 |
| Reduced PWP | 10 | 21.3 | 10.71 |

# Linear Time Varying MM

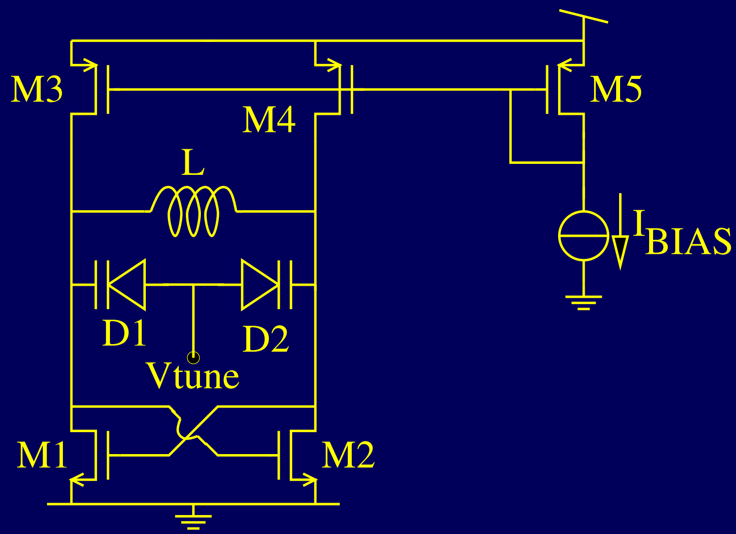
- Useful abstraction for some nonlinear systems
  - mixers, switching filters, samplers, DC/DC converters, ...
  - Leverage LTI methods (Krylov, TBR, ...)
  - frequency translation/TD nonlinear sampling captured
  - signal-path nonlinearities **not** captured
- Input-output relationship linear
  - but **not time-invariant**

# LTV MM on RF Mixer

- I-channel mixer and buffer block (Lucent ME W2013 RFIC)
- 360 nodes, signal upto 80KHz, LO at 178MHz
- LTV macromodel accuracy (<u>**Time-Varying Pade**</u>)
  - size 2: upconversion xfer fn matches to 300kHz
  - size 10: upconversion xfer fn matches to 400MHz!
- <u>**Speedup more than 500**</u>

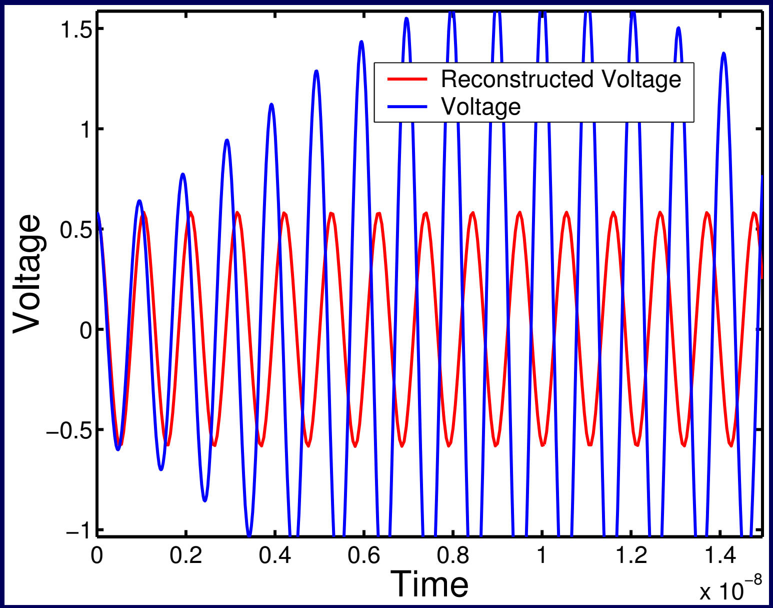
# Oscillators: Nonlinear MM

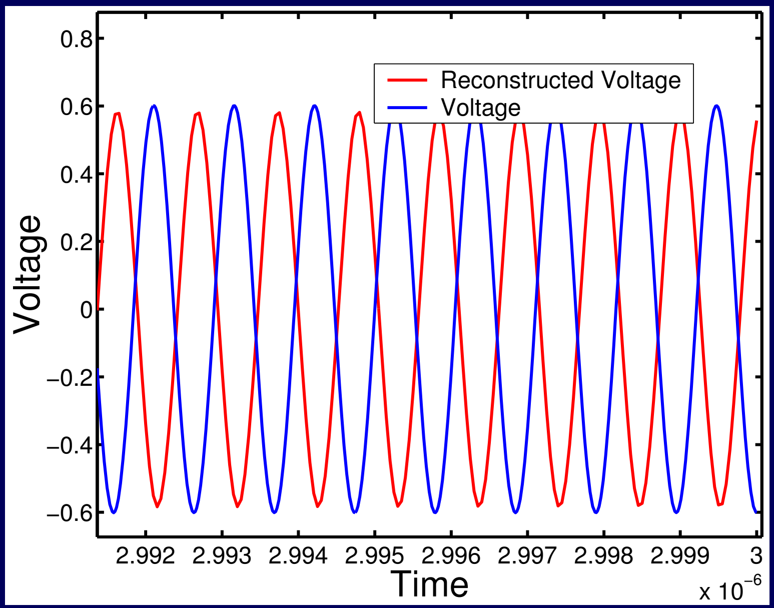



- **Critical in communication system designs**
  - VCOs, PLLs, LOs, synchronization, ....

- **Difficult for SPICE**: Inaccurate+extremely time-consuming
- Complex autonomous dynamics
- Existing hand-based macromodels miss qualitative phenomena
  - **injection locking**
- **Automated nonlinear MM**...

# Osc MM captures injection locking




Unlocked regime

Locked regime

**65x times speedup (for 2-node ckt); much greater for bigger oscillators**

# Nonlinear MM Progress

- Weak: JR (98), JRP (99-00), Li/Pileggi (NORM, 03)
- Strong: Rewienski/White (99-00), Dong/JR (03)
- LTV: JR/JRP (97)
- Oscillators: Li/JR (03)
- **Pockets of progress**
  - Not comprehensive like LTI
  - General problem **very difficult**
  - Dimensionality explosion (polynomial order, # regions)

# Summary/Conclusions

- Automated MM **will** become practical
  - future system designs need it
  - (still) young area, much potential
- Hard problem: no single method will solve it all
  - pockets of elegant, useful, broadly applicable mathematical methods...
  - ...plus application-specific, roll-up-your-sleeves methods
  - Need to patch together **all approaches for useful, practical solutions**

# Summary/Conclusions

- **Common, open, easy-to-use infrastructure** important: coalesce everyone's contributions
  - Significantly more complicated algorithms, better structuring, modularity **needed**
  - Open standards: avoid further balkanization of analog EDA

# Summary/Conclusions

- Litmus test:

  **Designer acceptance and involvement**

  "Despite all of the benefits associated with analog top-down design, there remains a strong resistance against adopting this methodology. Many analog designers (at least so far) are content to maintain the status quo. Because most of the tools are new, many designers are unaware of their availability. This lack of awareness is further compounded by a natural resistance to change long-established procedures. Additionally, there's a learning curve associated with the new analog tools." - EE Times, 2001

# Acknowledgments

- Joel Phillips, Ning Dong
- Ken Kundert, Jacob White, Peng Li, Larry Pileggi, Rob Rutenbar
- many others