Analog and Mixed Signal Verification for Communications

-- the role of Automated Macromodelling

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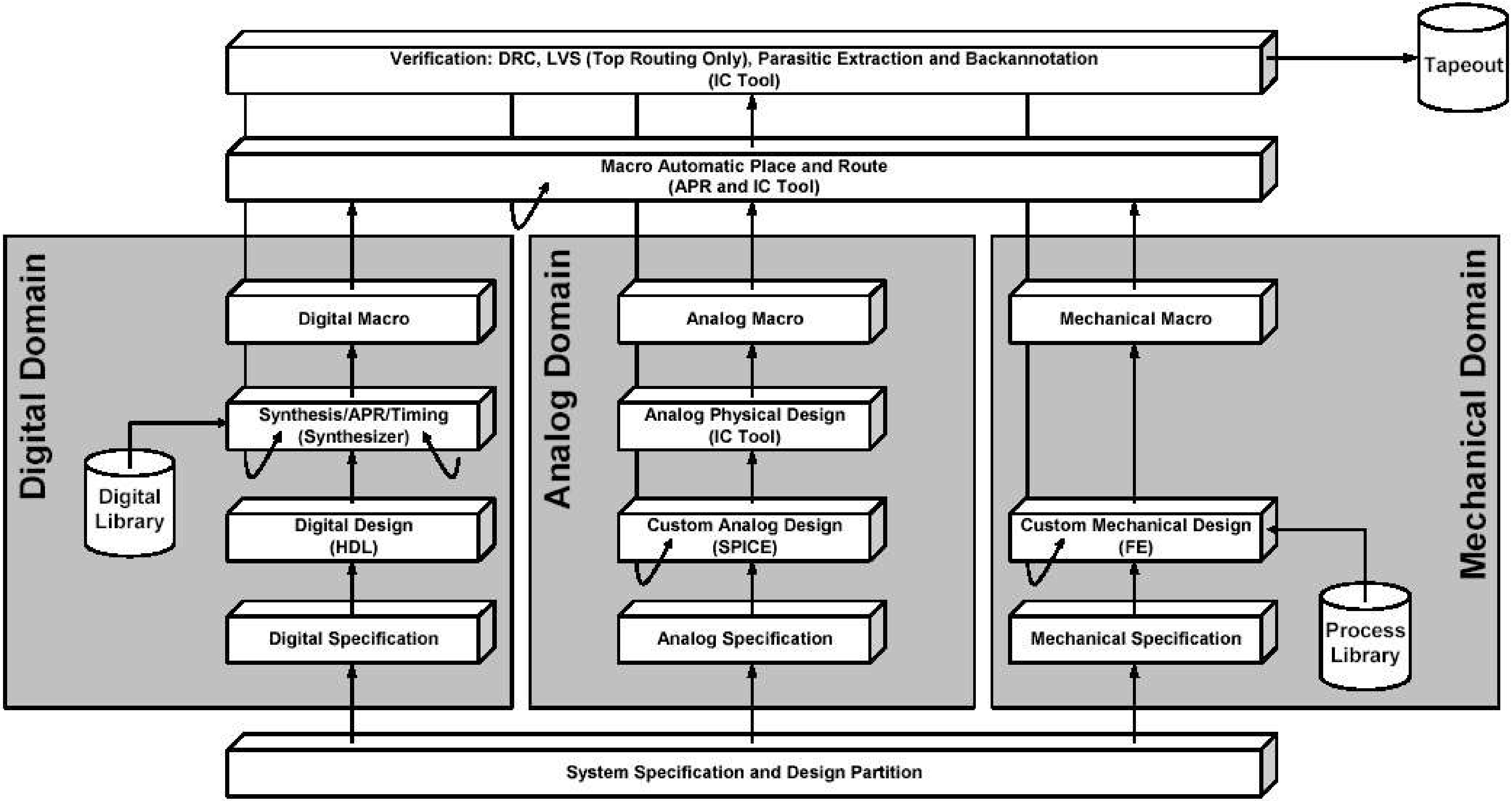
Automated Macromodelling

- What and Why
- Background: LTI Macromodelling
- Nonlinear Macromodelling
- Interference Noise Macromodelling
- Oscillator Macromodelling

Today's bottom-up design

McCorquodale et al, U of Michigan



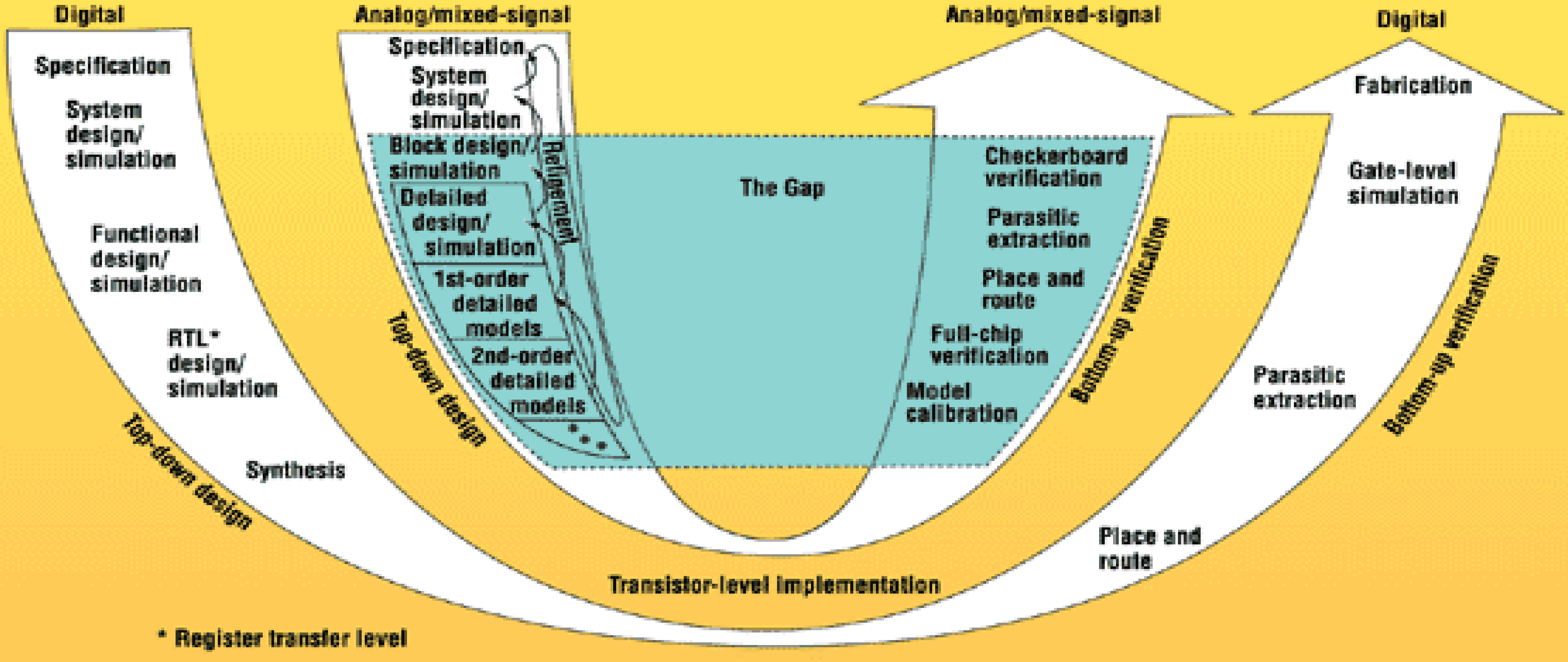
- 3-5 spins=cutting edge; >10 at Lucent

Mixed-Signal 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
- **<u>Impossible at SPICE level</u>**

“The Gap”

EE Times

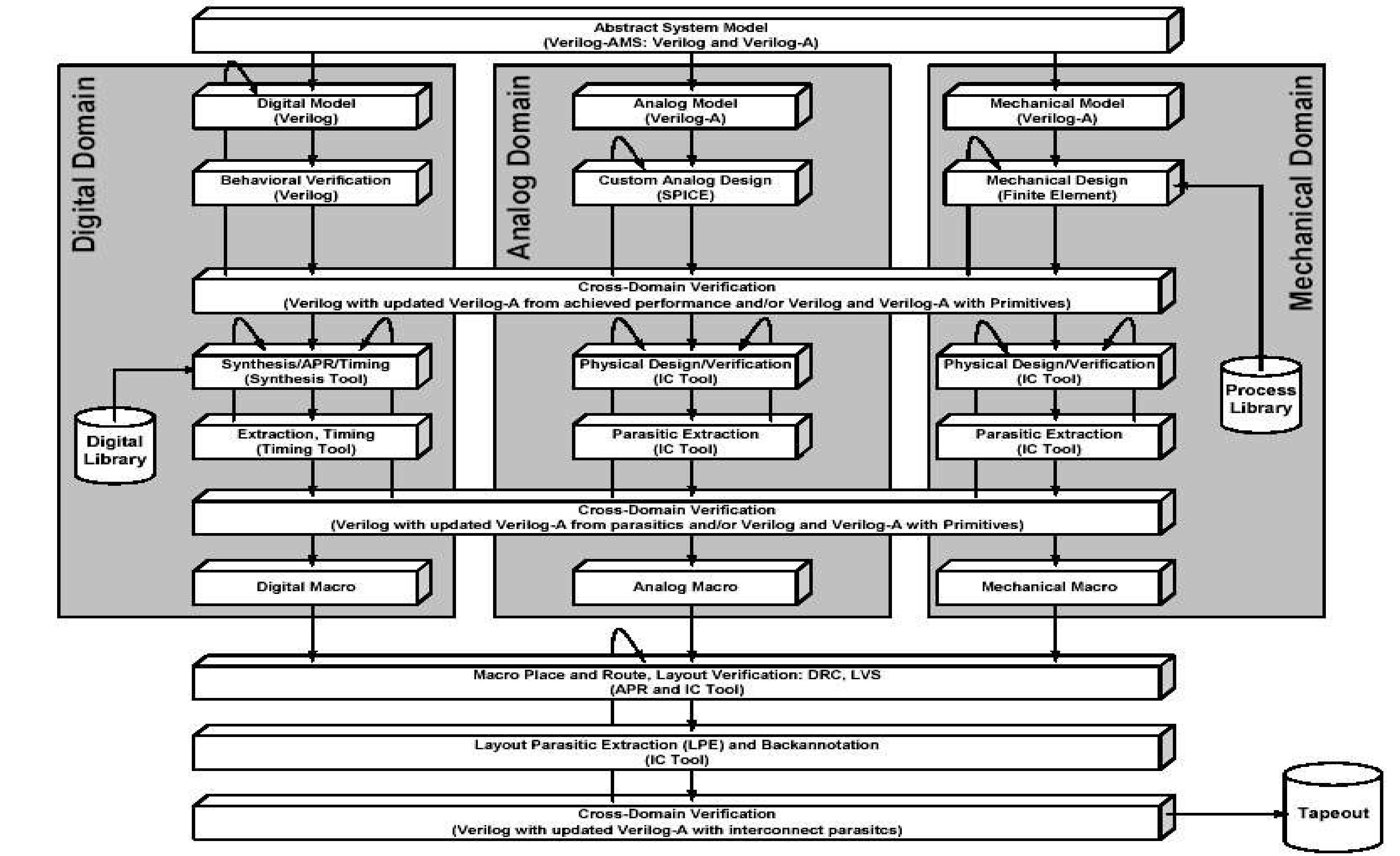


“The primary problem hindering the change to analog top-down design and bottom-up verification has been the lack of tool support for the design process between system-level specification and transistor-level implementation, as well as between transistor implementation and chip fabrication. These missing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

“The Gap”

- **Solution: Good bottom-up macromodels**

Top-Down Design



Generating Macromodels

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

Automated Macromodelling

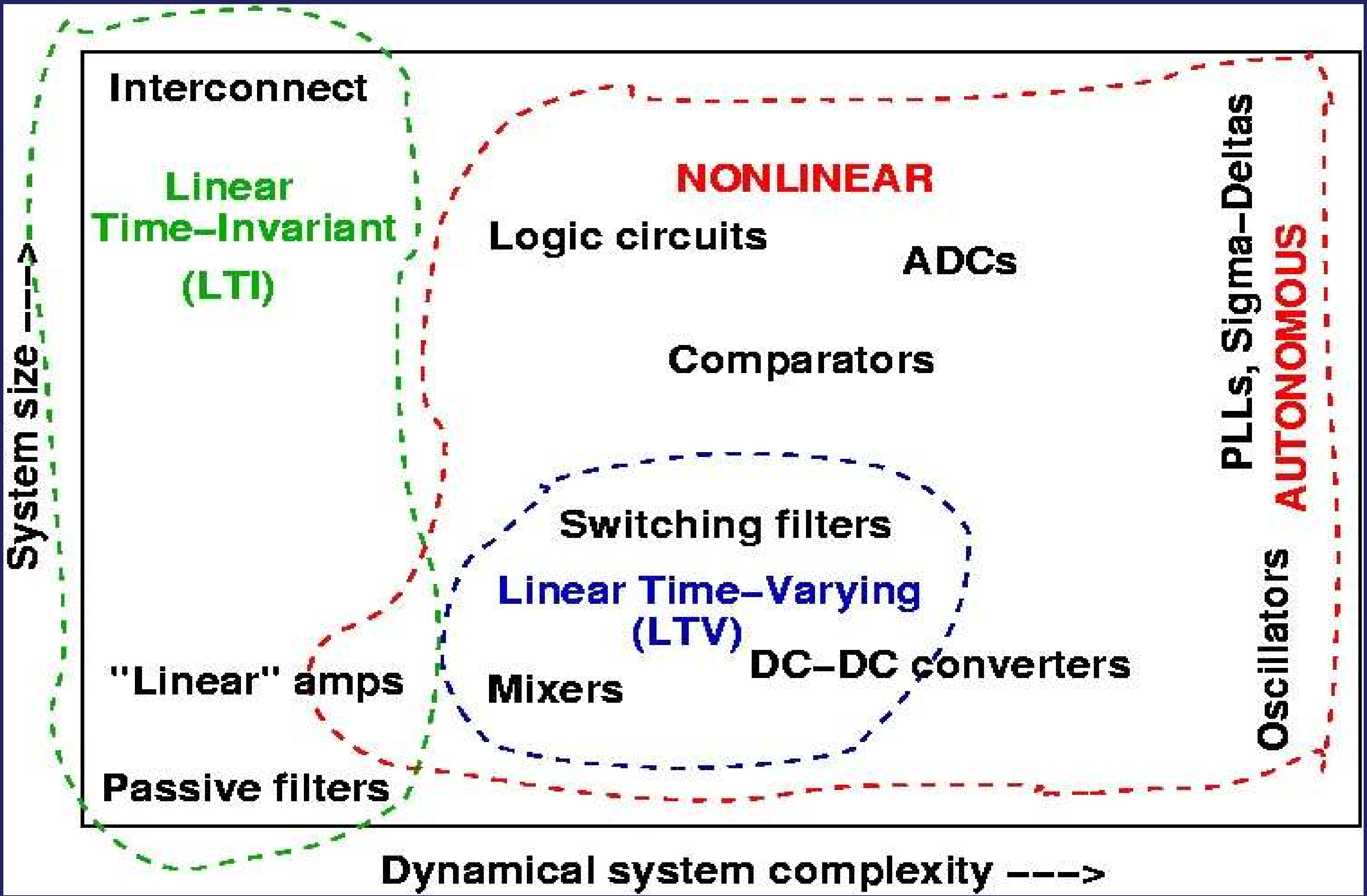
- The dream: **push-button bottom-up model generation**
  - a.k.a Rob's Red Button: “**go make my macromodel**”
  - prescribed accuracy guaranteed
  - trade off **speed vs accuracy**
- Needed for design sustainability
  - complexity exceeds manual ability to keep up

“The Gap”

“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

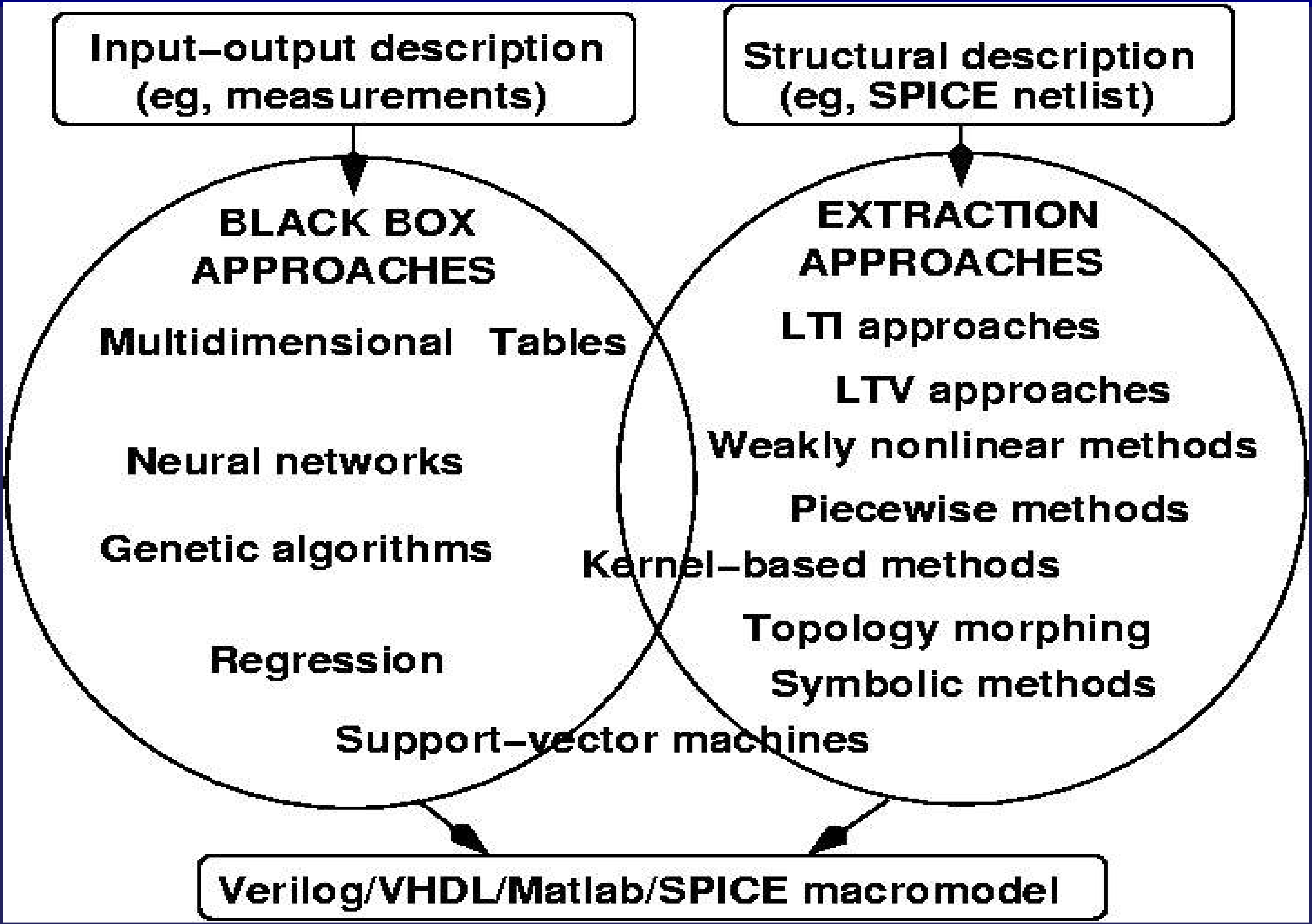
Why Difficult?



Approaches to Macromodelling

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

Automated MM Approaches



“Algorithmic” Macromodelling Approaches

- **Mathematical algorithms** based on theory
- **Provably preserve some useful property**
  - eg, moments of transfer function
- **AWE:** first prominent method (LTI)
- Variety of nonlinear, LTV methods
- **Generally applicable** (eg, multi-physics)
  - not specific to a particular type of circuit/topology
  - eg: same oscillator MM technique works as well for a Colpitts oscillator as for a DFB laser or a grandfather clock

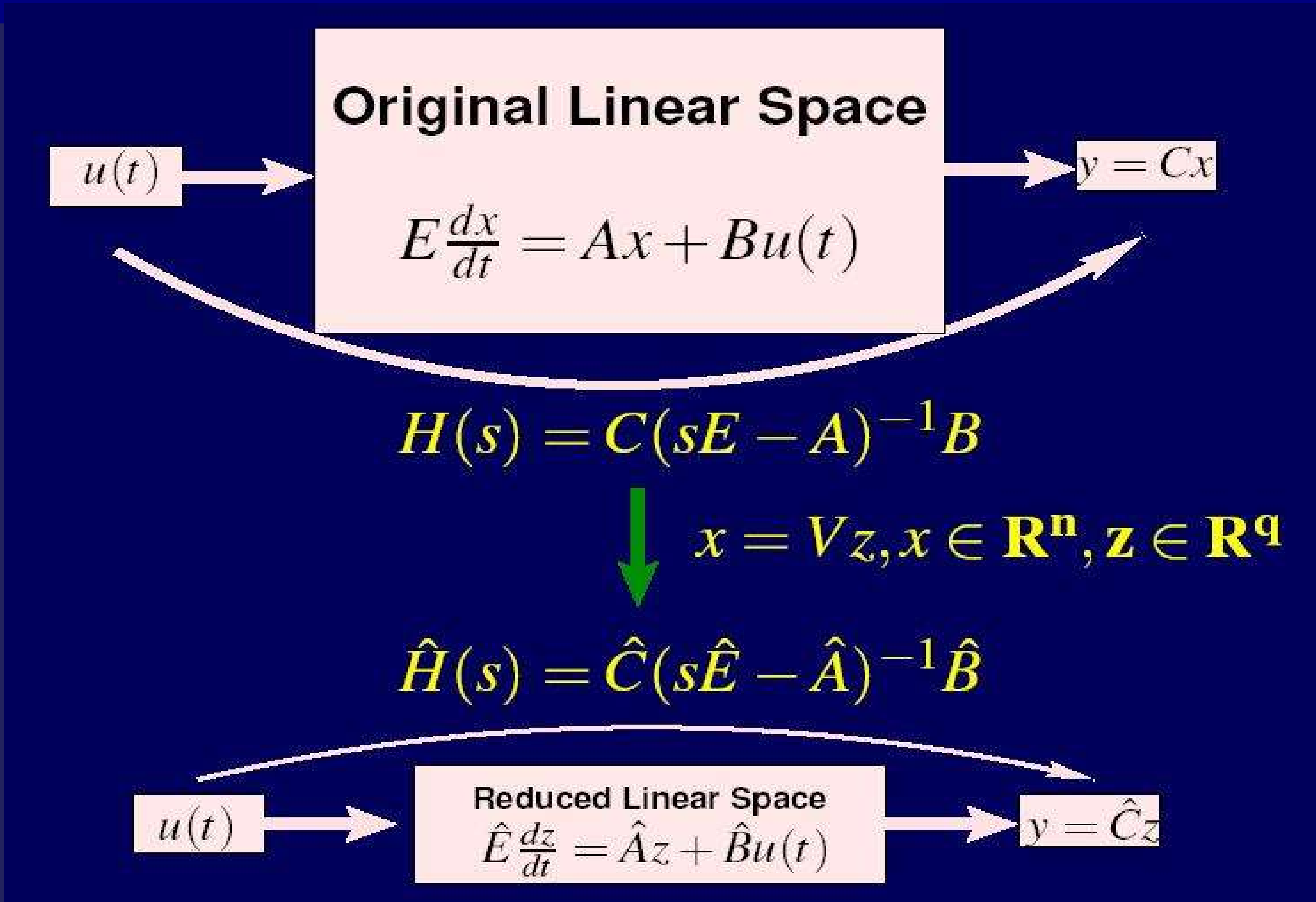
Types of Algorithmic Macromodelling

- **Linear Time Invariant (LTI)**
  - application: interconnect (delay, crosstalk)
  - AWE, PVL, PRIMA, TBR
- **Linear Time Varying (LTV)**
  - mixers, sampling/switching circuits, (oscillators)
- **Weakly nonlinear (Volterra)**
  - companding ckts, amplifier/mixer gain compression
- **Strongly nonlinear (stable)**
  - everything else: comparators, switching, slewing, ...
- **Autonomous**
  - oscillators, PLLs, etc.: marginally stable

Linear Time Invariant Systems

- What is LTI?
  - Scale input waveform => scale output waveform
  - Time-shift input => 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

LTI Macromodel Generation



Asymptotic Waveform Evaluation

- AWE (Pillage/Rohrer ~1990)
- **Preserve moments** of LTI transfer function
  - frequency-domain xfer-fn derivatives
- **Explicit moment matching**
  - calculate moments of original system
  - run a Pade approximation: small rational function
  - map to small dynamical system macromodel

LTI MM Accuracy/Stability

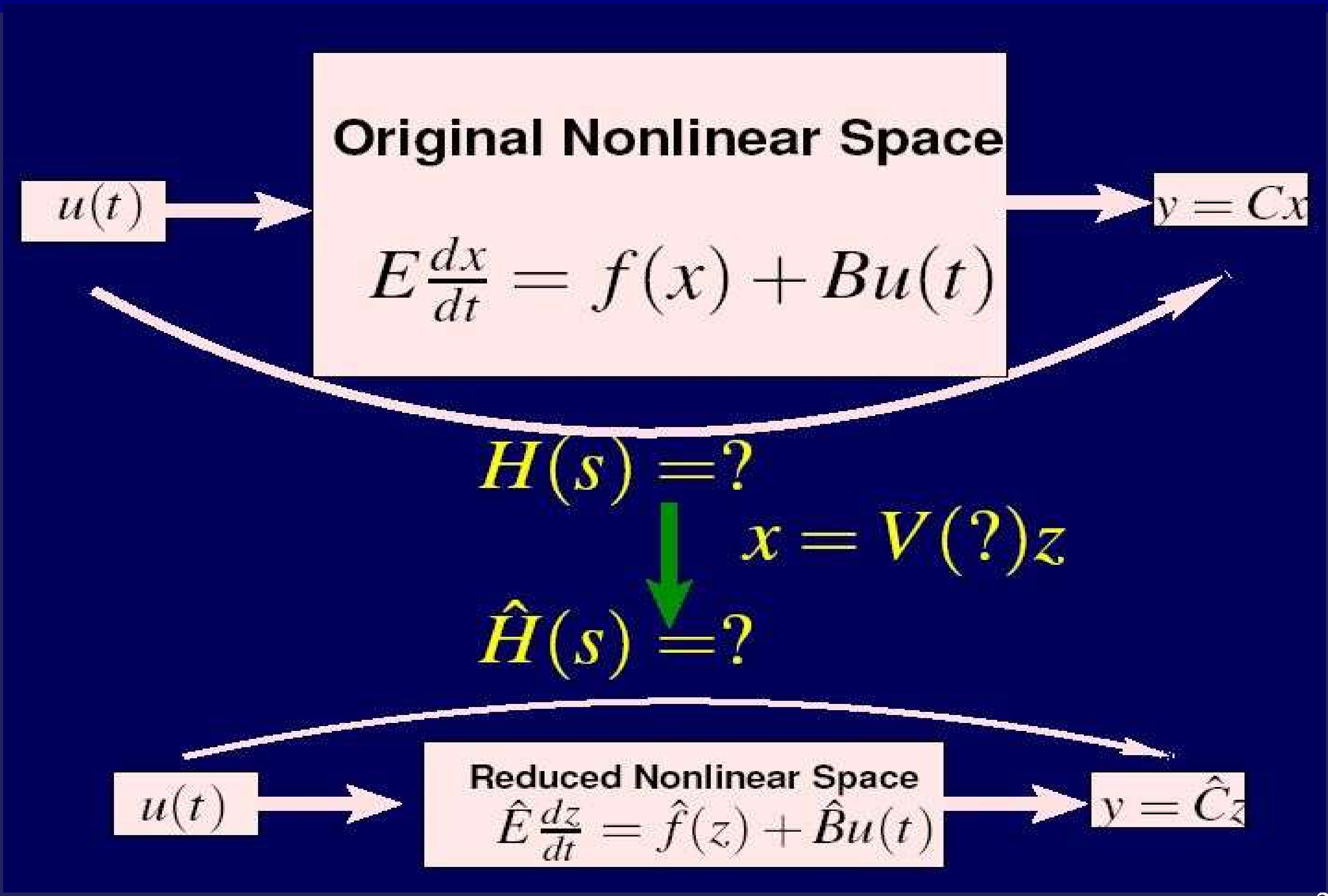
- **Increasing size does not increase accuracy**
  - explicit moment generation, Toeplitz-matrix based calculation numerically ill-conditioned
- **Implicit moment matching:** Krylov subspace methods
  - don't calculate moments: generate related Krylov subspaces robustly (Lanczos/Arnoldi methods)
  -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

LTI MM Summary

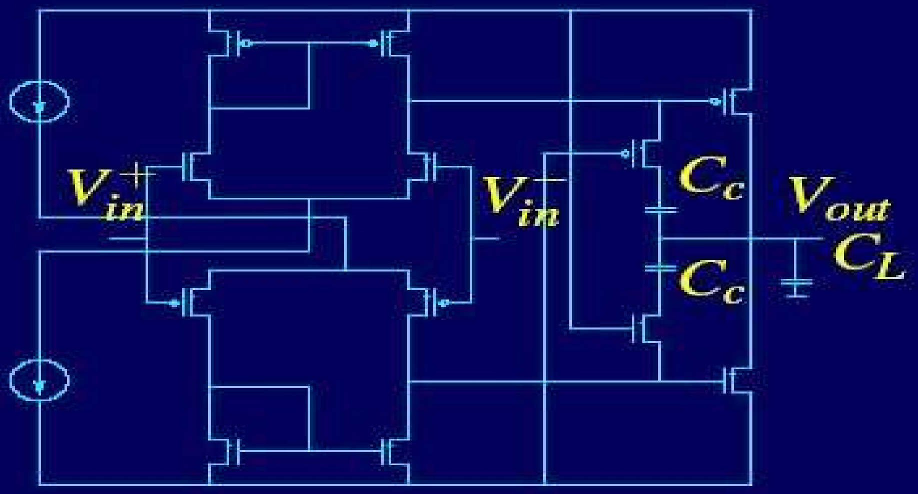
- **Important features**
  - Accuracy vs size tradeoff
  - MM scalability
  - MM passivity
- **Computational properties**
  - AWE, Krylov methods linear with system size
  - TBR methods cubic (but new results from Joel!)
- **Relatively mature and practically usable**
- **Basis for nonlinear approaches**

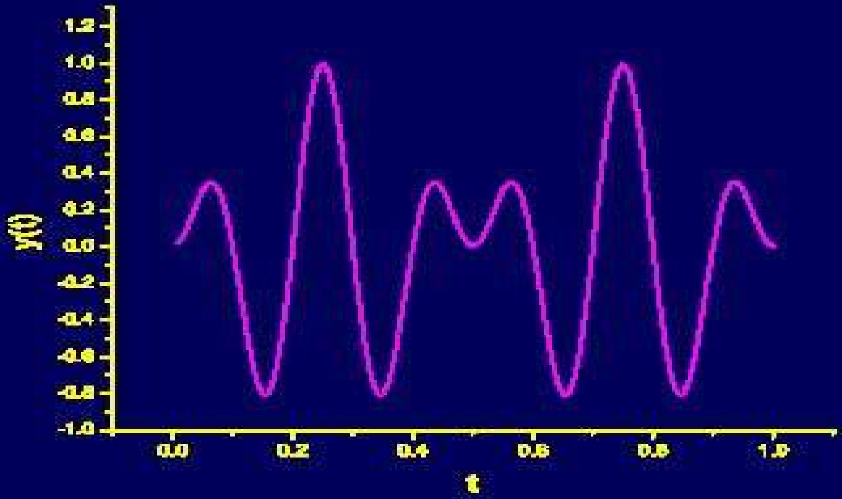
Macromodelling Nonlinear Systems

Nonlinear Macromodel Generation

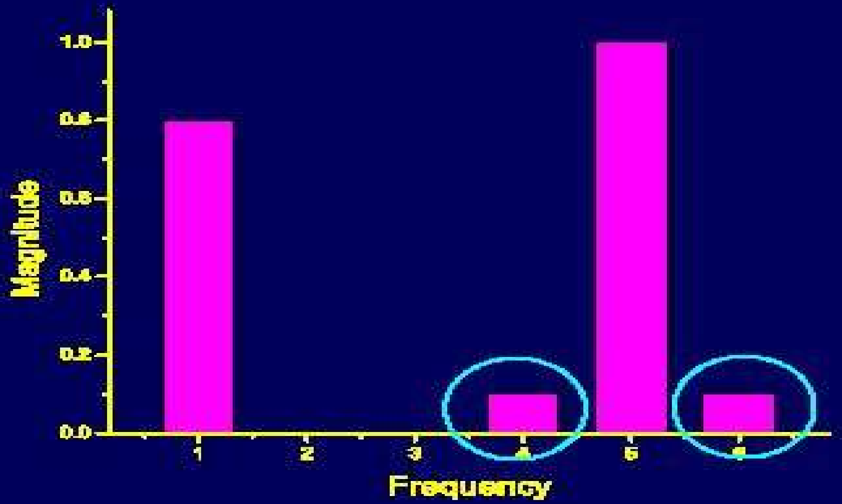


Weakly Nonlinear Systems



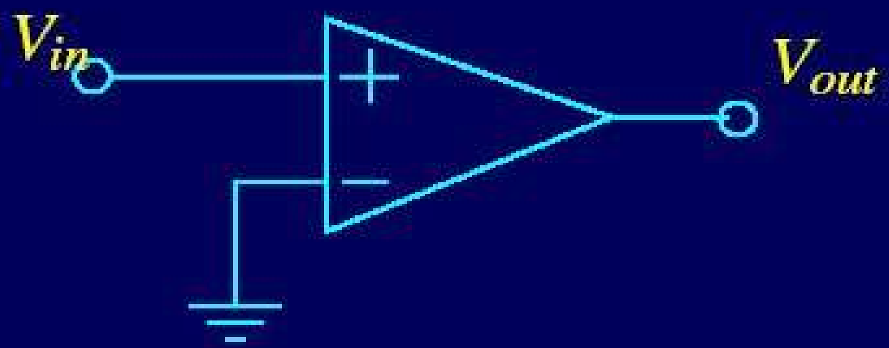


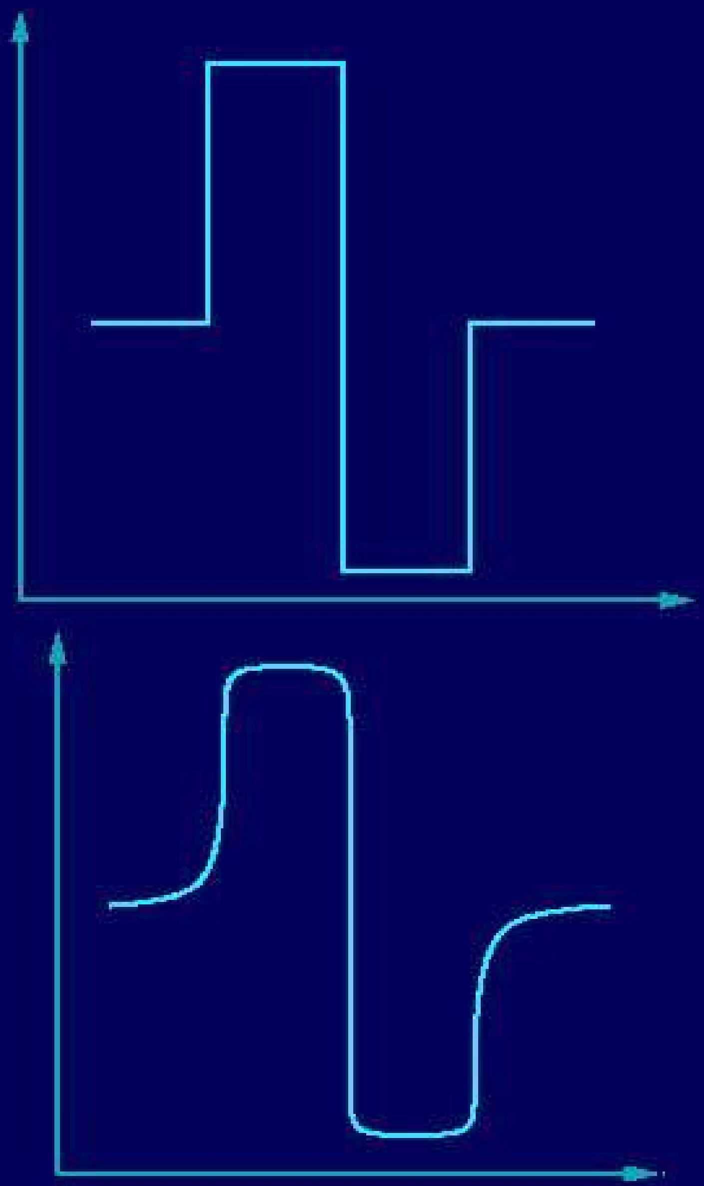
- Distortion, IM important!
- Must capture small distortion/IM



Strong Nonlinearities

Comparators, switching mixers

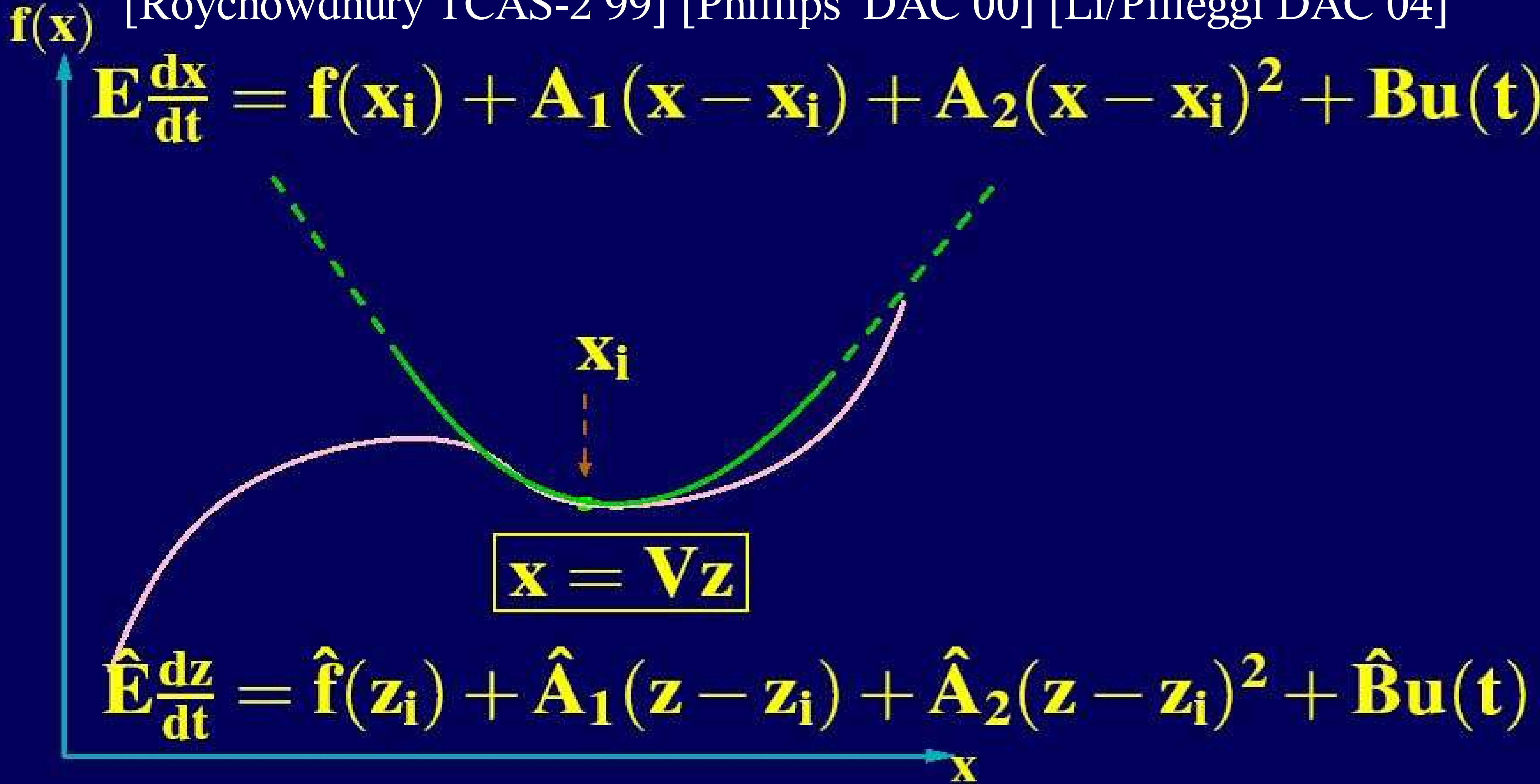




- Large signal clipping
- Must capture strong nonlinearities

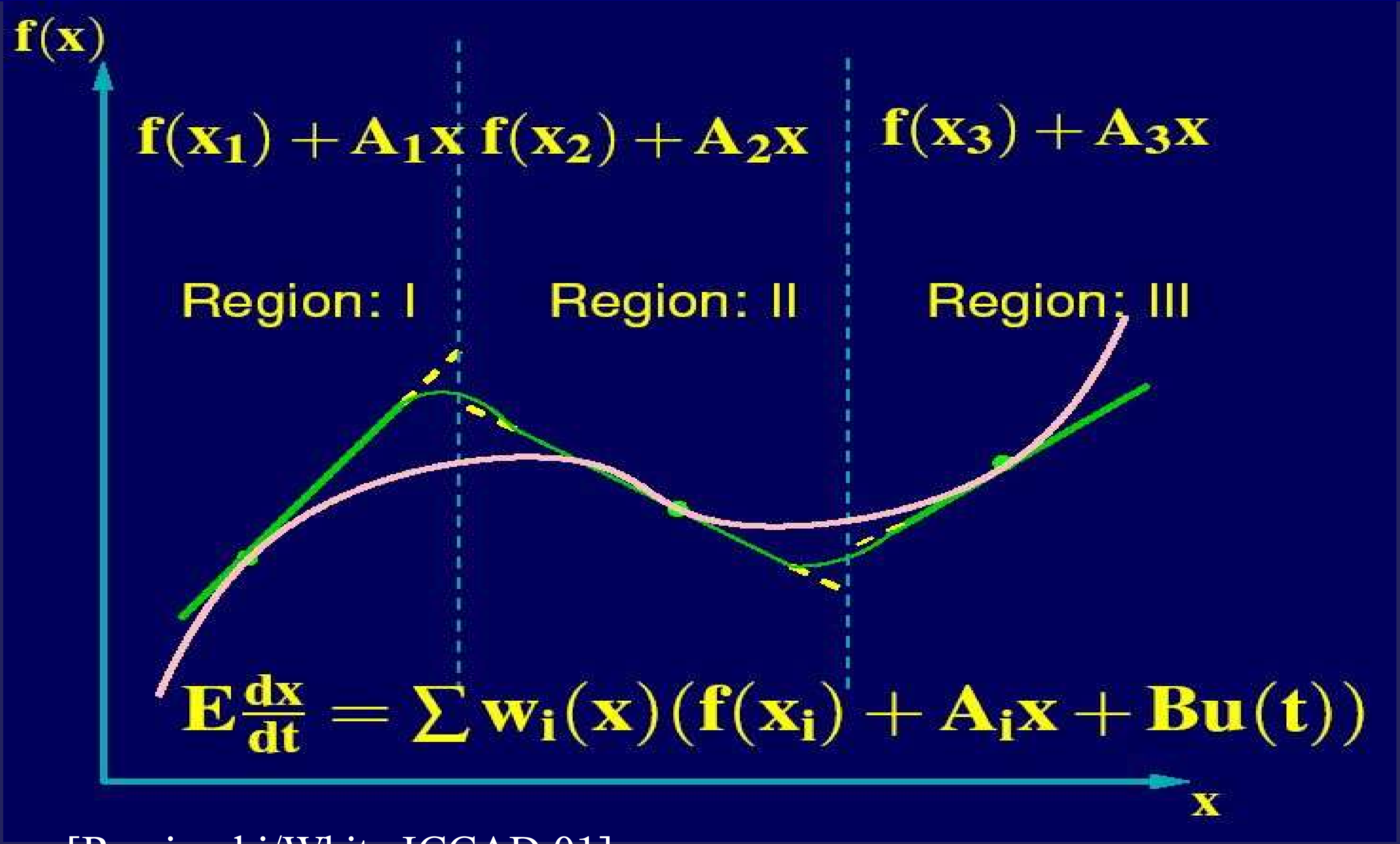
Polynomial (Volterra) Reduction

[Roychowdhury TCAS-2 99] [Phillips DAC 00] [Li/Pilleggi DAC 04]



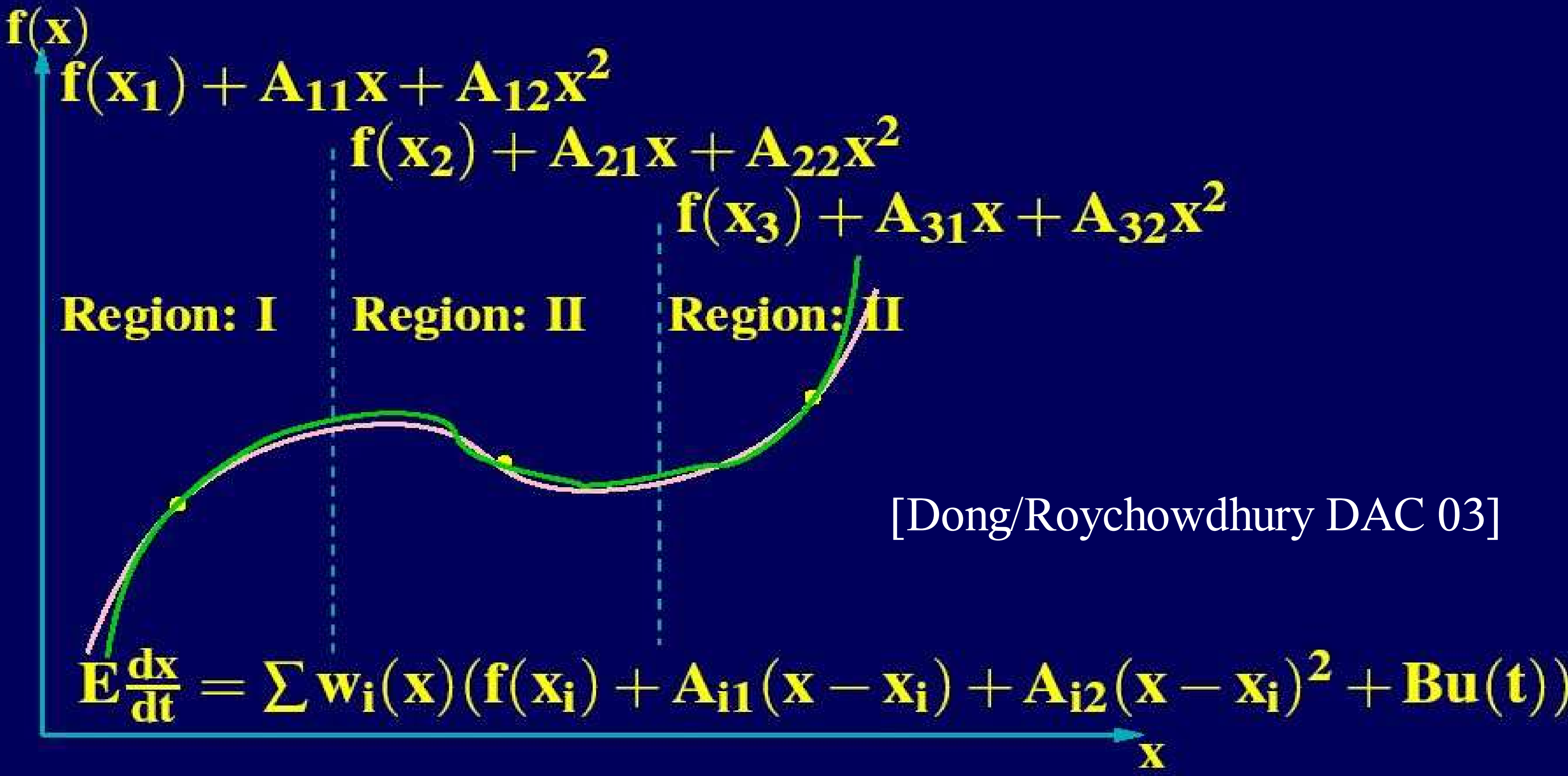
- **Good for small distortion, Poor for large swing**

Trajectory Piecewise Linear MM



[Rewienski/White ICCAD 01]

Piecewise Polynomial Macromodelling

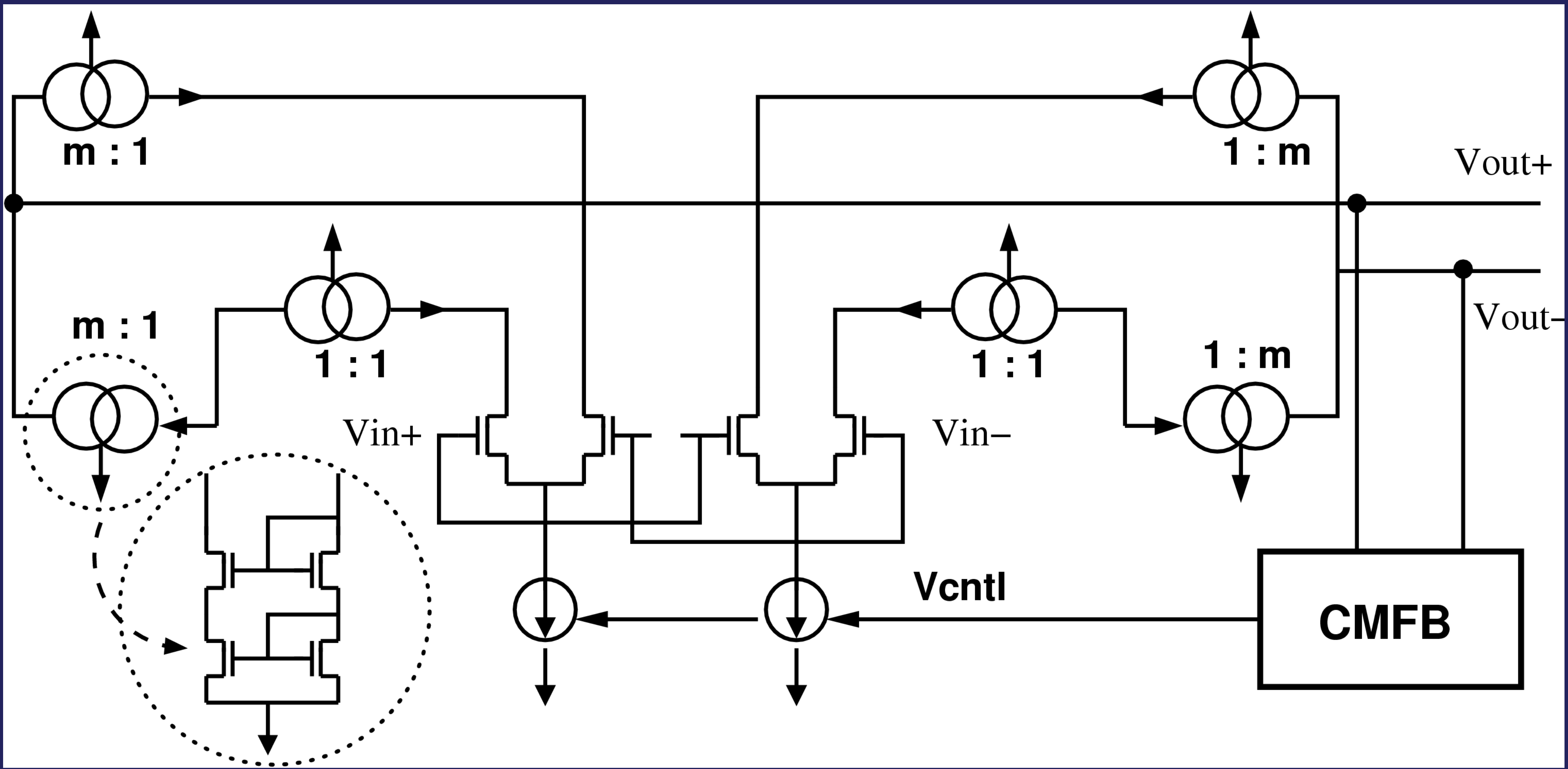


- Good for small distortion, also good for large swing

Drop-in Replacement Macromodels

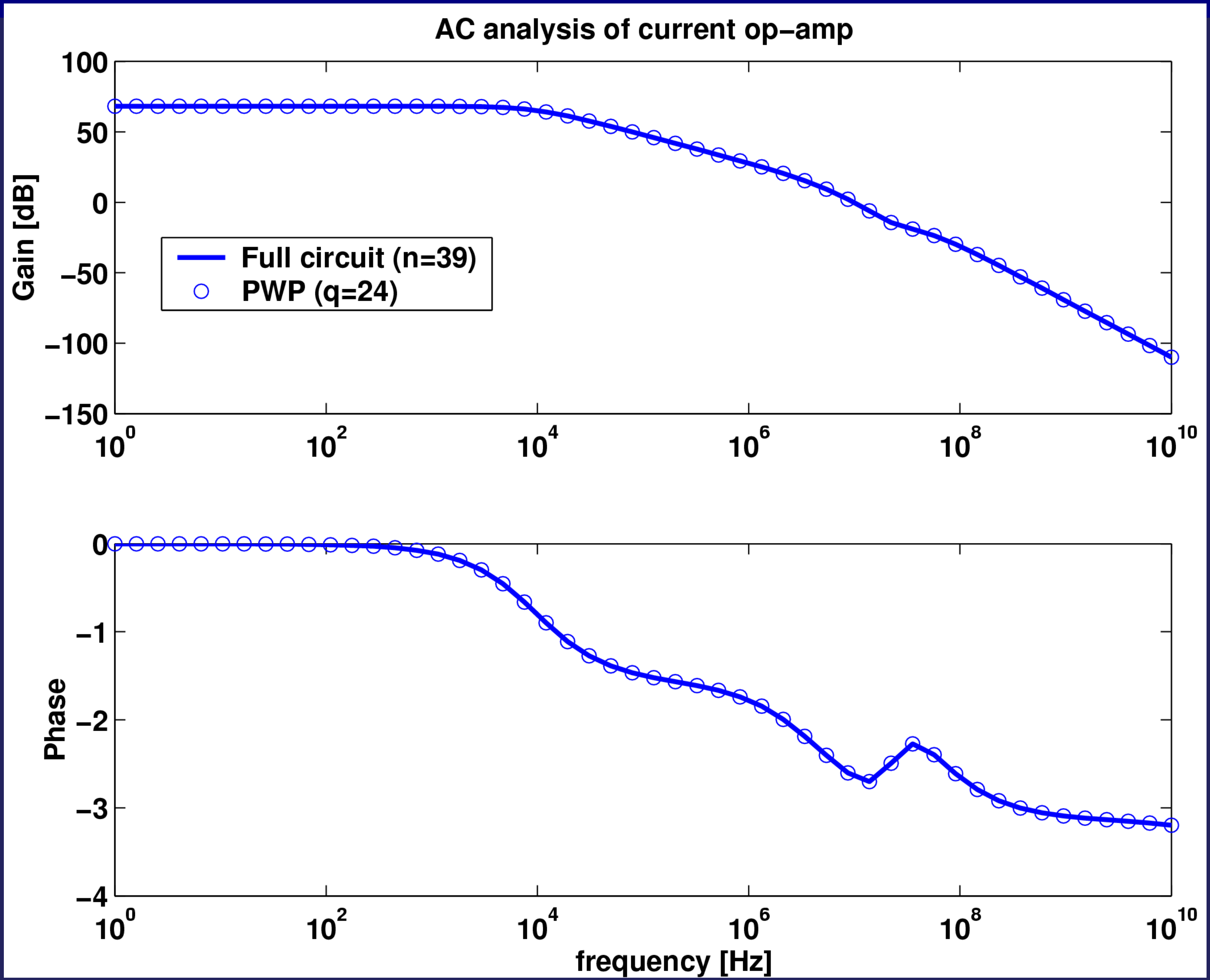
- Design process typically runs many simulations
  - DC (sweep), AC, small-signal distortion, transient
  - time- and frequency-domain analyses
- Would like one extracted macromodel to work for all analyses
  - ie, a drop-in replacement for the original
  - PWP-generated macromodels: good candidates

Current Mirror Op-Amp

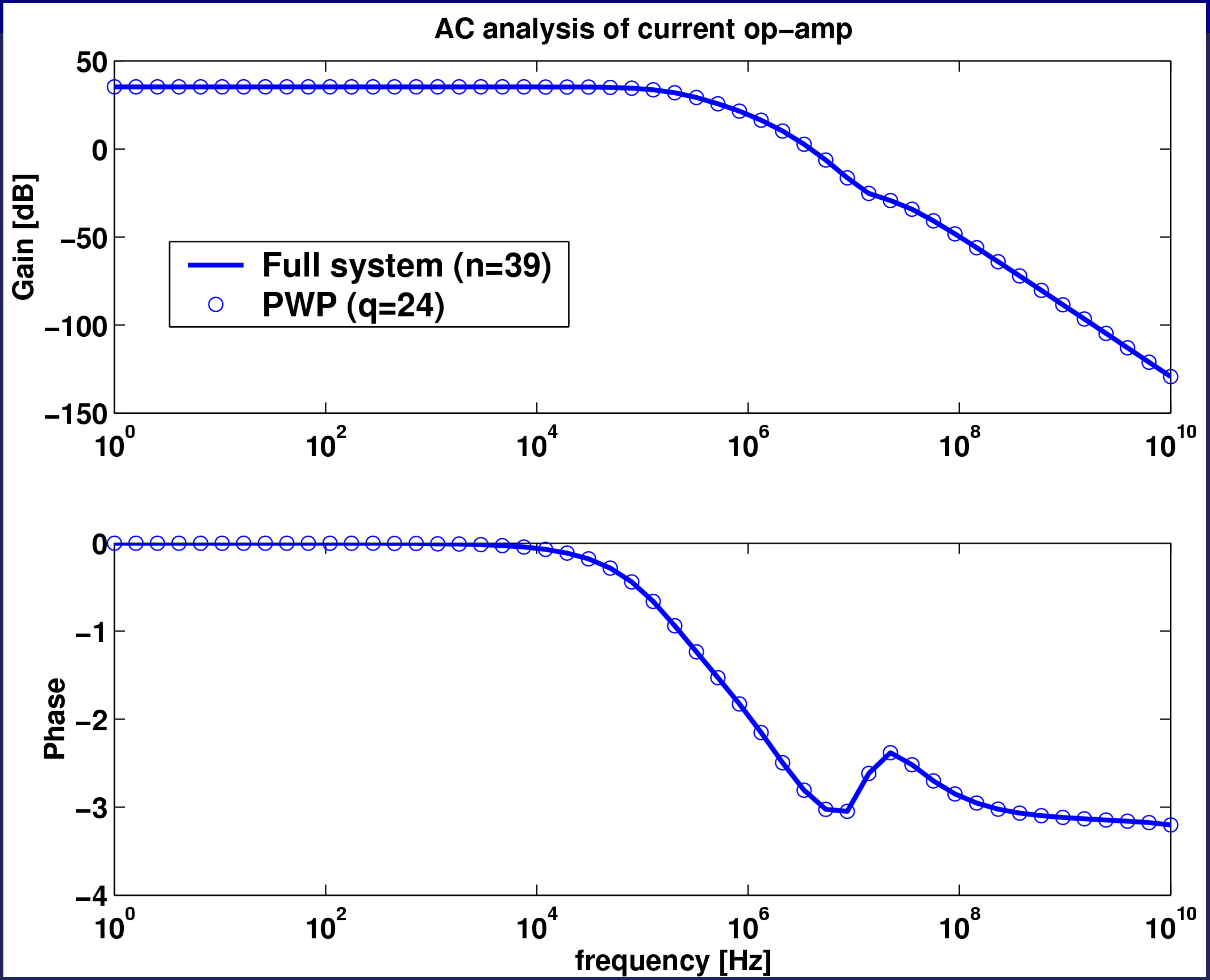


Original: ~50 MOSFETs. Macromodel size: 19, 27 regions

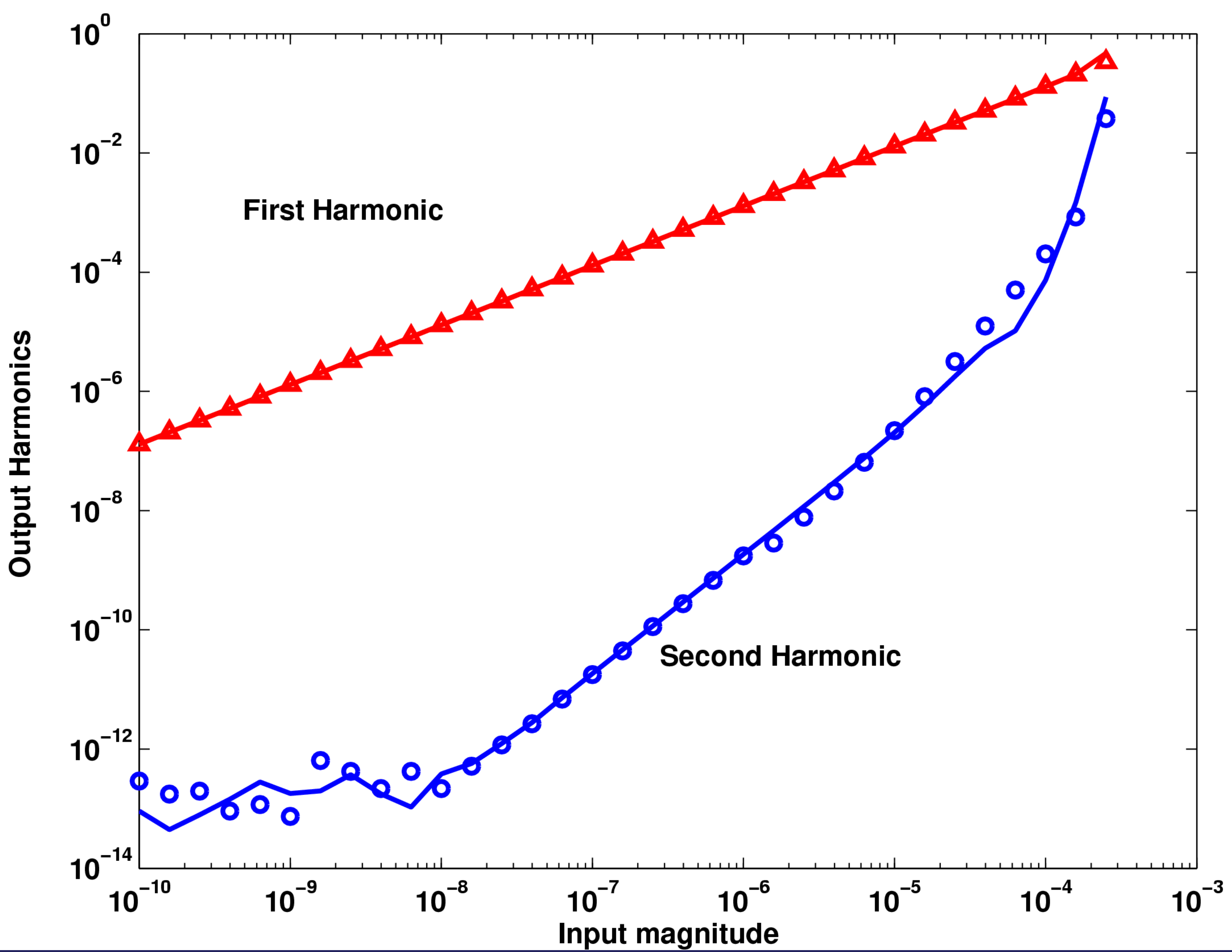
Macromodel vs Original: AC Sweep 1



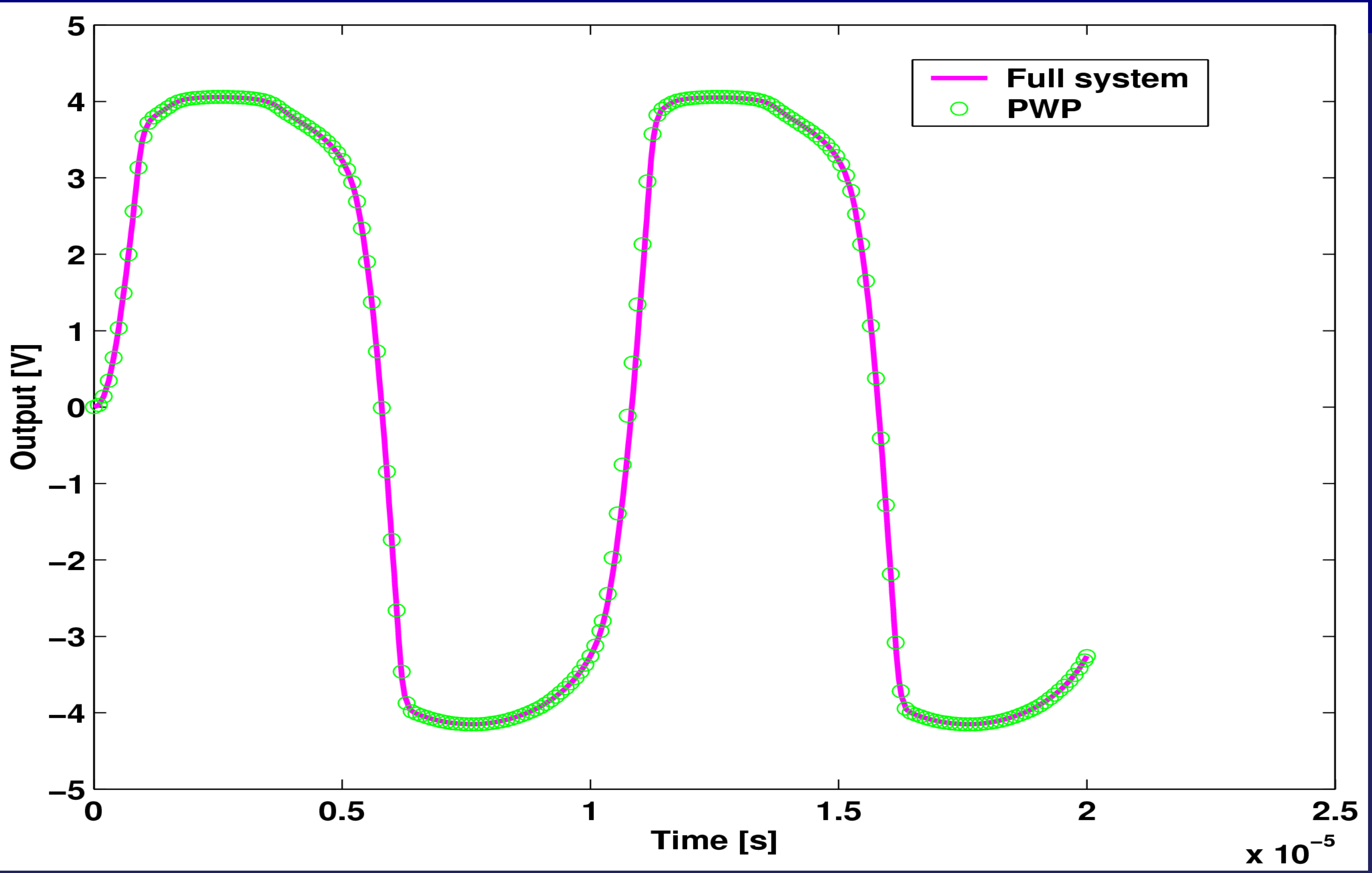
Macromodel vs Original: AC Sweep 2



Macromodel vs Original: Distortion

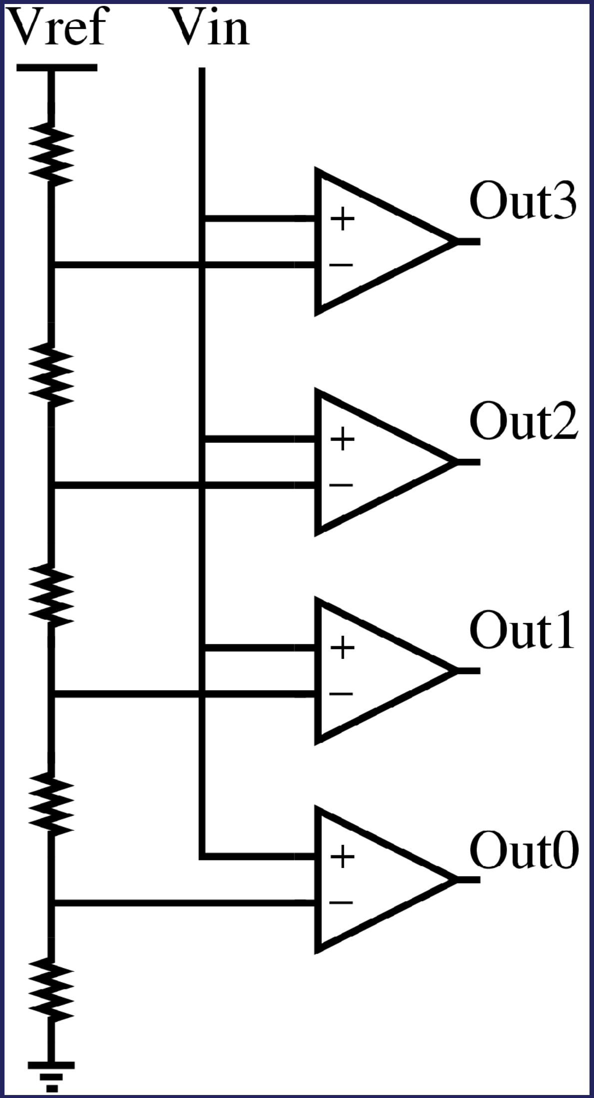


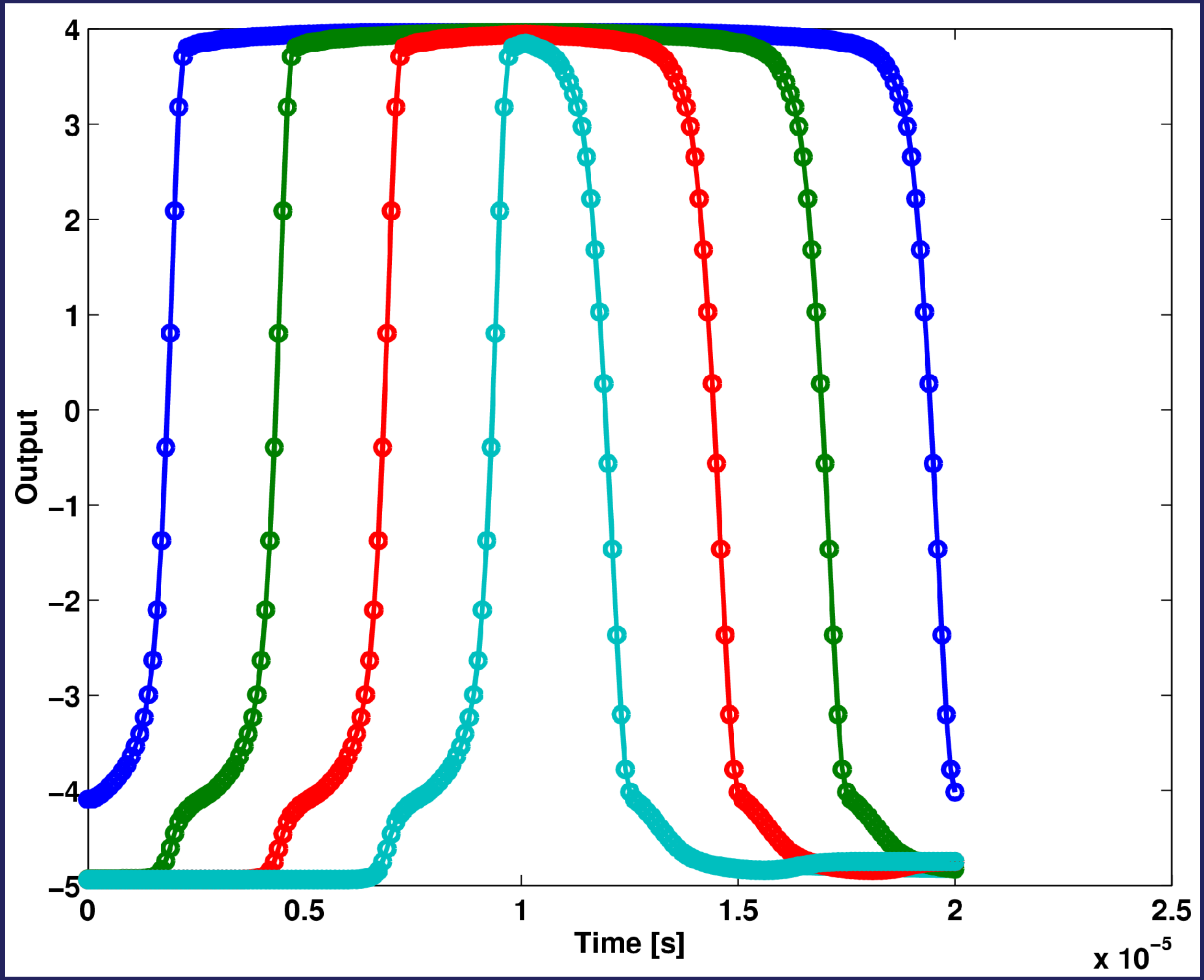
Macromodel vs Original: Transient



- ***speedup: 41x over original***

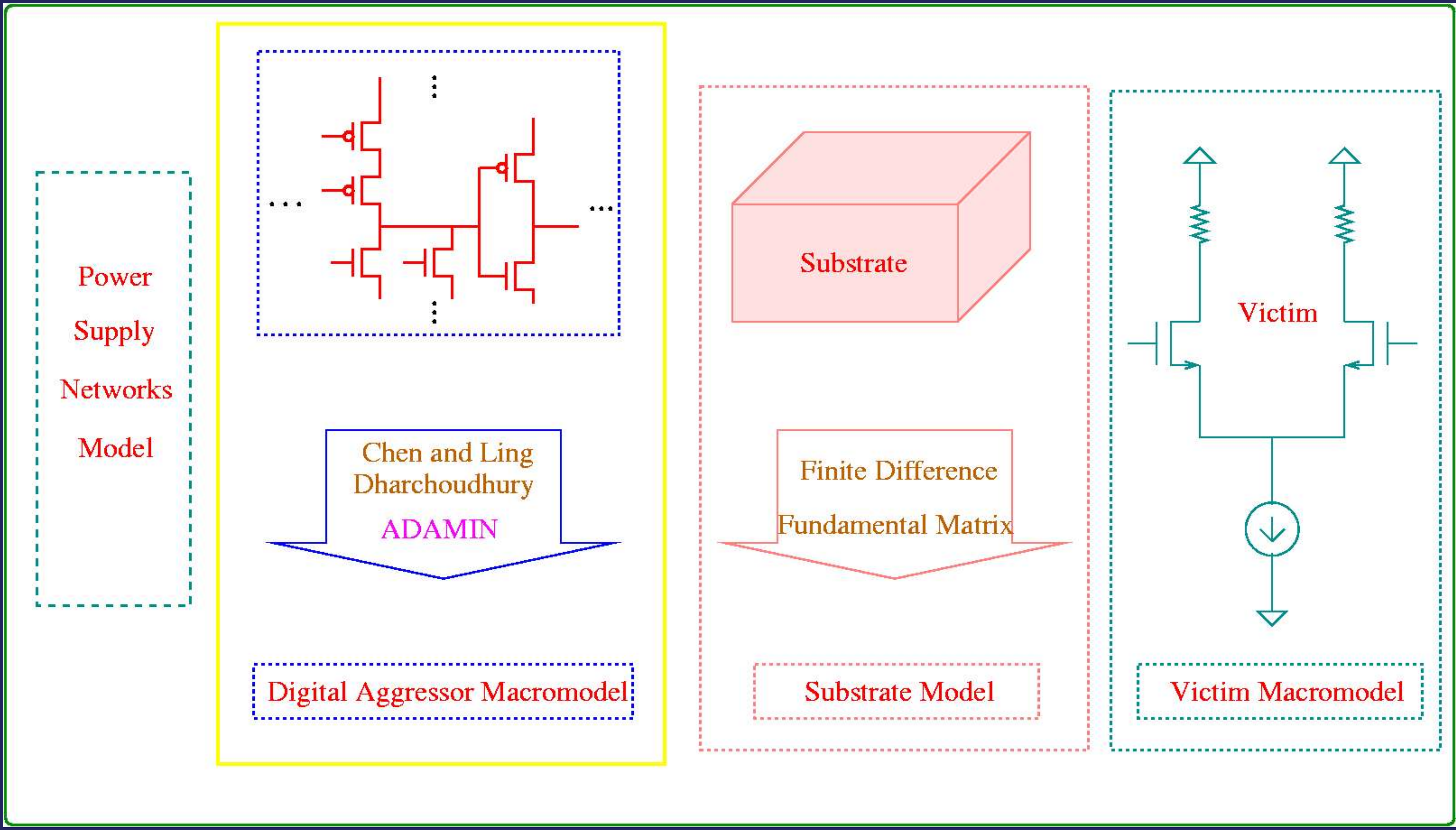
Small ADC: System-level Simulation



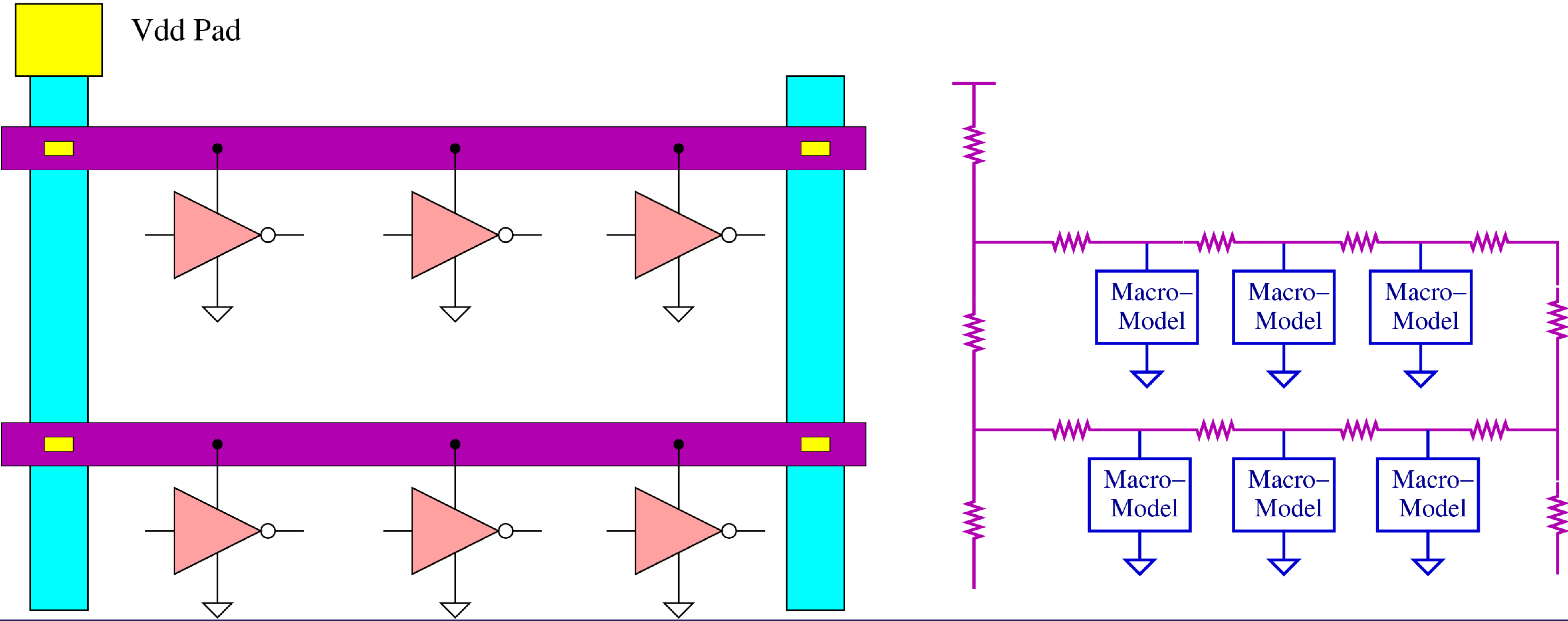


Excellent match between original and macromodel

The Mixed Signal Interference Noise Problem



Macromodelling Digital Noise Injection



- Interested only in interference injection characteristics
  - supply and substrate injections: analog waveforms
  - digital signals: system time variation
  - LTV model captures switching behaviour well!

[Wang/Murgai/Roychowdhury DATE04]

Linear Time-Varying Macromodelling

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

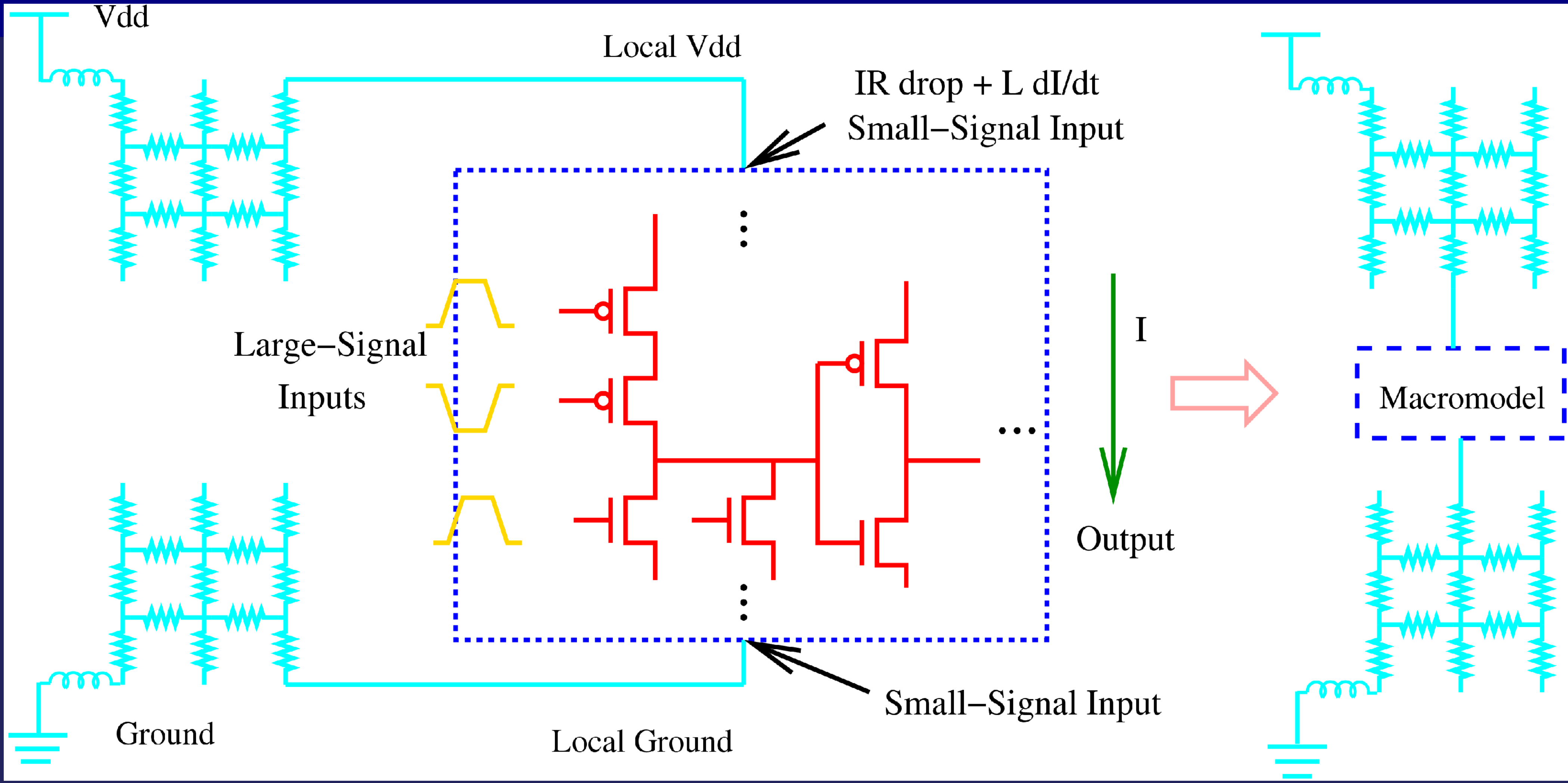
Basic Principles of LTV Macromodelling

- LTV systems have time-varying (but linear) transfer functions
  - LTI transfer function H(s) --> H(t,s)
    - t captures system time variation
    - s captures input/output time variations
  - computationally useful form of H(t,s):
    - linear matrices C(t) and G(t): from transient simulation/steady state calculations

$$H(t_1,s) = d^T \left(\frac{\partial}{\partial t_1} C(t_1) + sC(t_1) + G(t_1) \right)^{-1} [b]$$

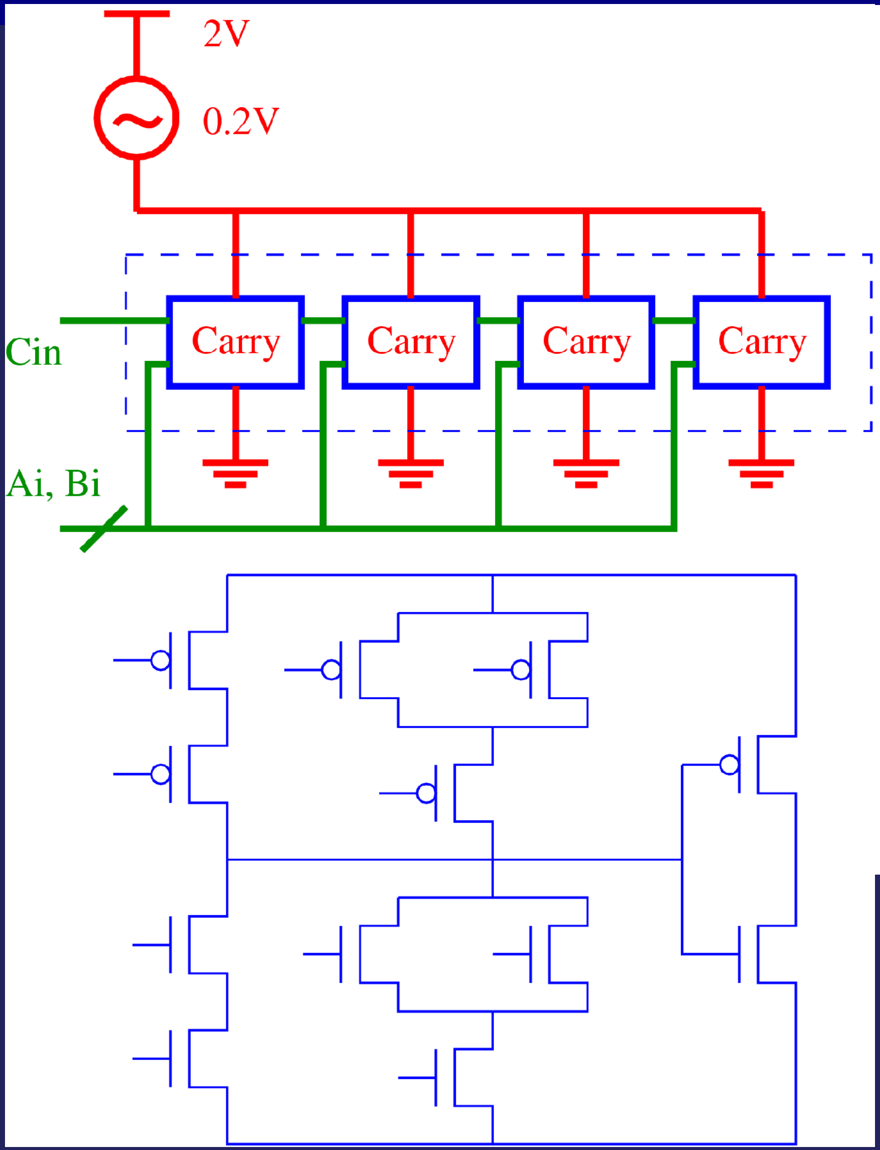
[Roychowdhury, Phillips ICCAD 98] [Roychowdhury TCAS-2 99]

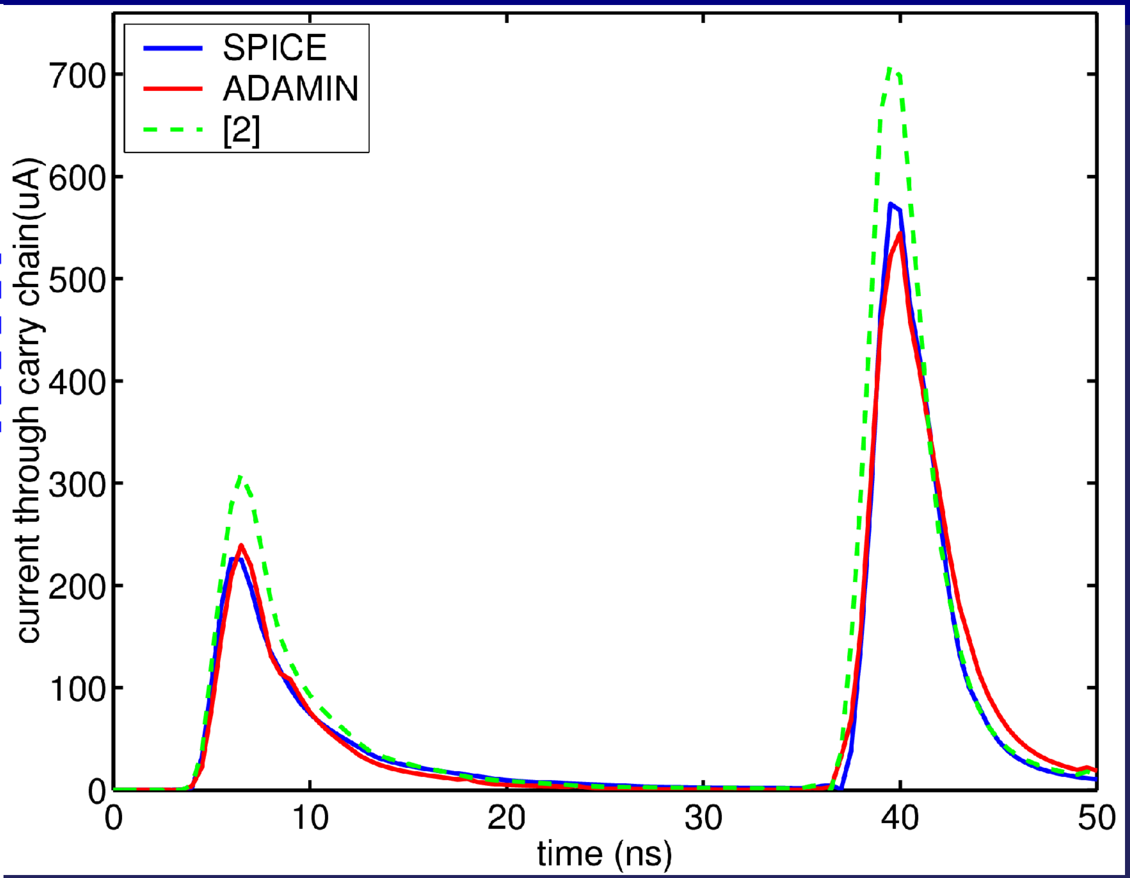
LTV Digital Aggressor Macromodels



- Input: (eg) power supply voltage variation
- Output: resulting current variation
- MM: small time-varying system relating input to output

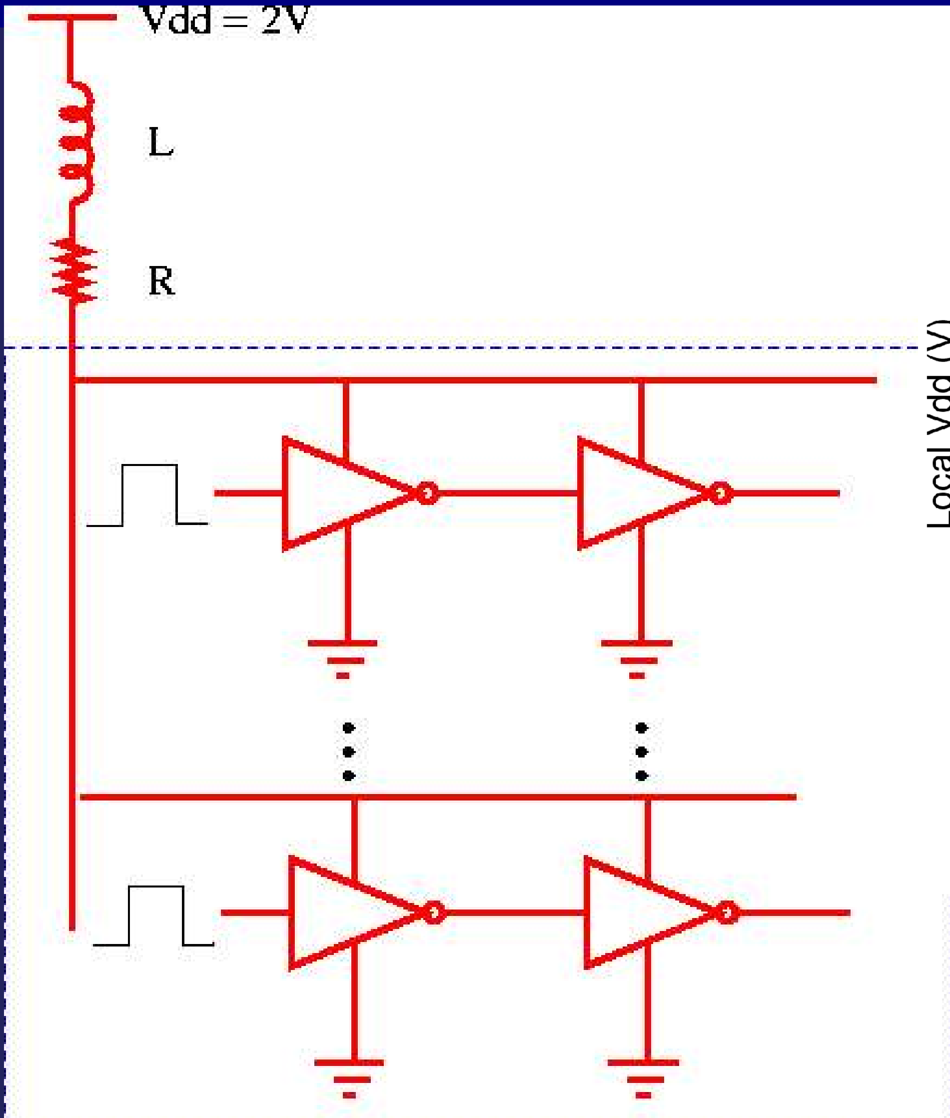
Supply-noise Induced Currents: Carry Chain

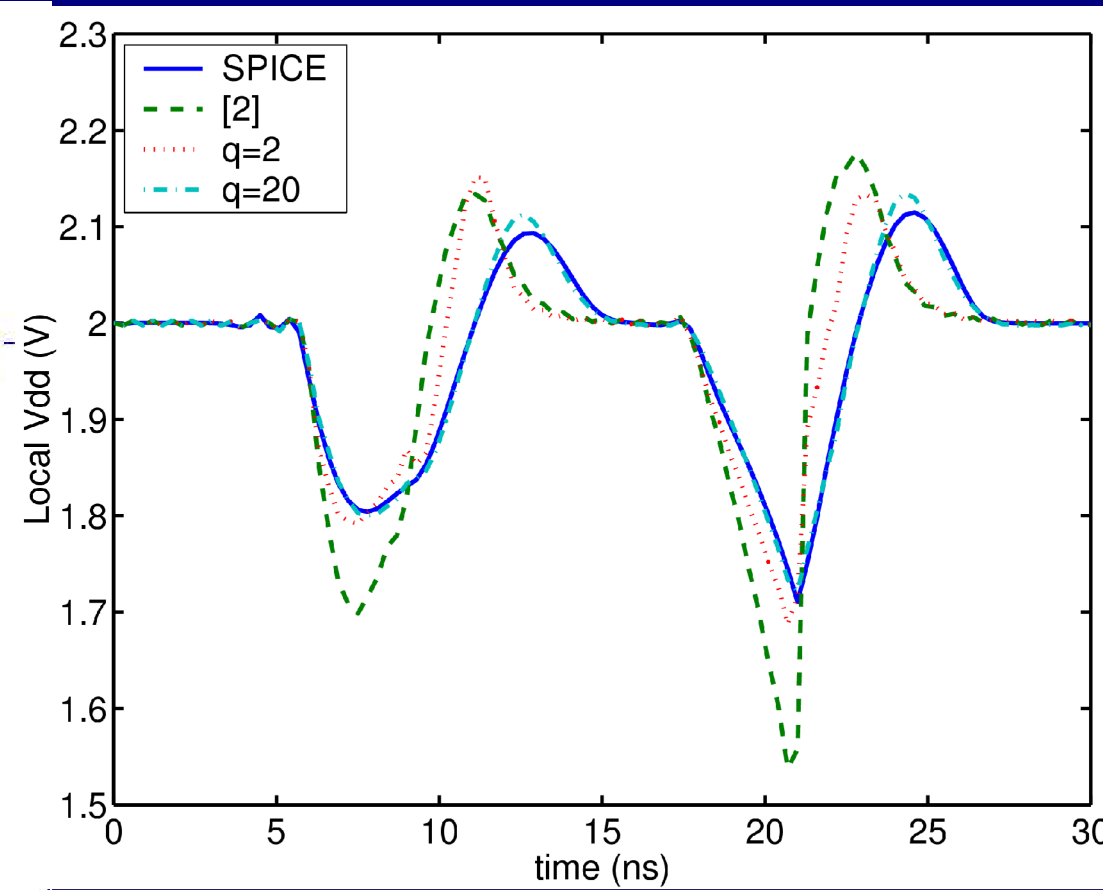




- Considerable accuracy improvement over current-source macromodel [Dharchoudhury 98]

"System" Simulation with Inductive Supply



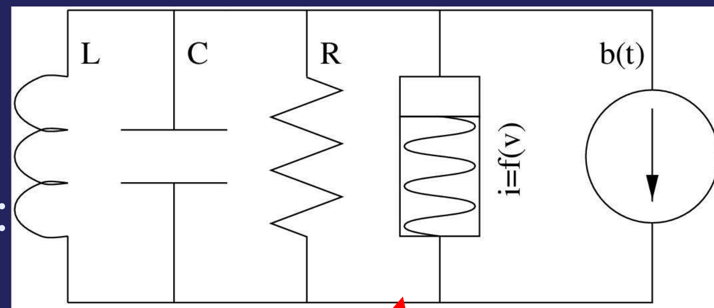


- size 2 MM: already better
- size 20: much more accurate
- 17000x speedup for 8000 gates

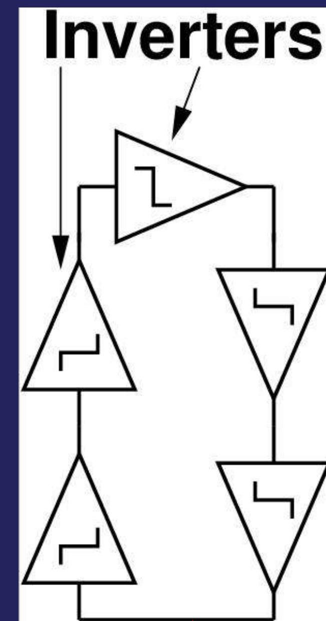
Macromodelling Oscillatory Systems

Oscillators

- Oscillators are critical in communication systems:
  - LC oscillators
  - Ring oscillators
  - Used everywhere:
    - VCOs, PLLs
    - CDR ckts
    - synchronization loops
  - ***<u>Very slow</u>*** to simulate
  - ***<u>Noise prediction problematic</u>***
- Needed:
  - Accurate/fast oscillator macromodelling capability
  - Accurate oscillator jitter/phase noise prediction



-ve feedback LC oscillator

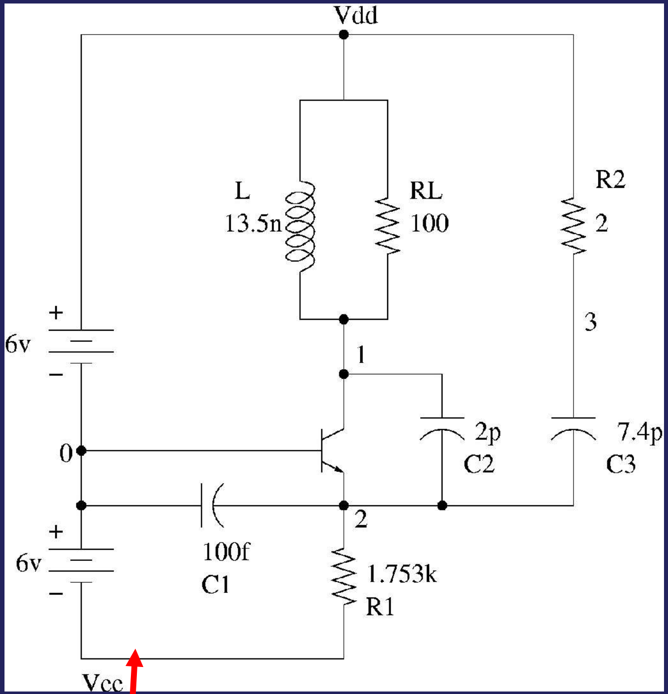


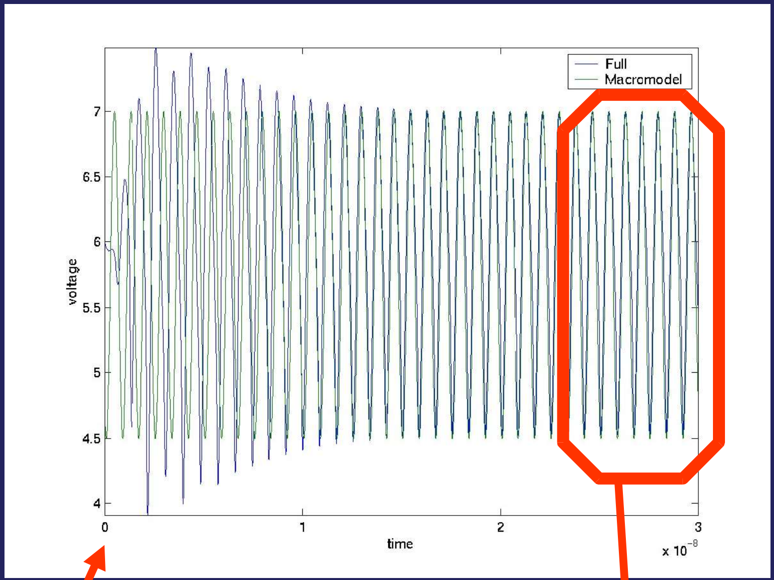
Ring oscillator

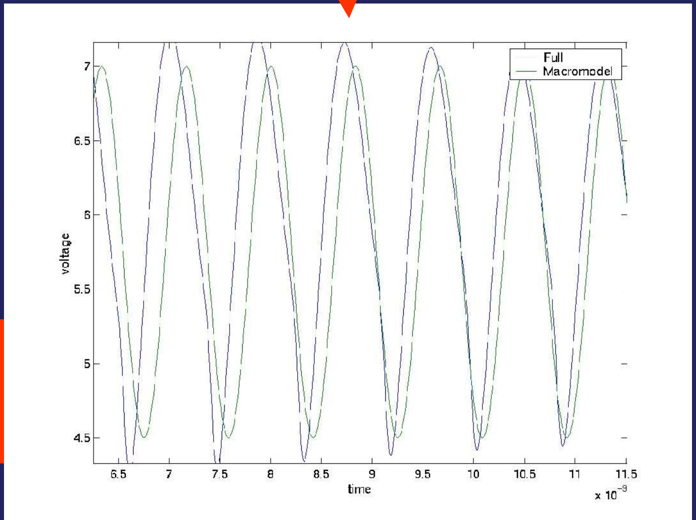
Why Oscillators are a Special Simulation Challenge

- Computation/size/accuracy: much greater than amps/mixers
- Even 1-transistor oscillators (eg, UHF oscs, >100GHz)
  – long startups, tiny timesteps needed
- On-chip RF: 100s to 1000s of transistors
  – VERY challenging to simulate
- Macromodelling offers dramatic speedup
  – Even for 1-transistor oscillator
- Oscillators feature complex phenomena: injection locking
  – oscillator's frequency “locks” to frequency of external input
  – if frequencies close enough, even if input is very small
  – can take extremely long to simulate
  – universal phenomenon: grandfather clocks, fireflies flashing, etc

Capturing Injection Locking in a Colpitts (LC) Oscillator







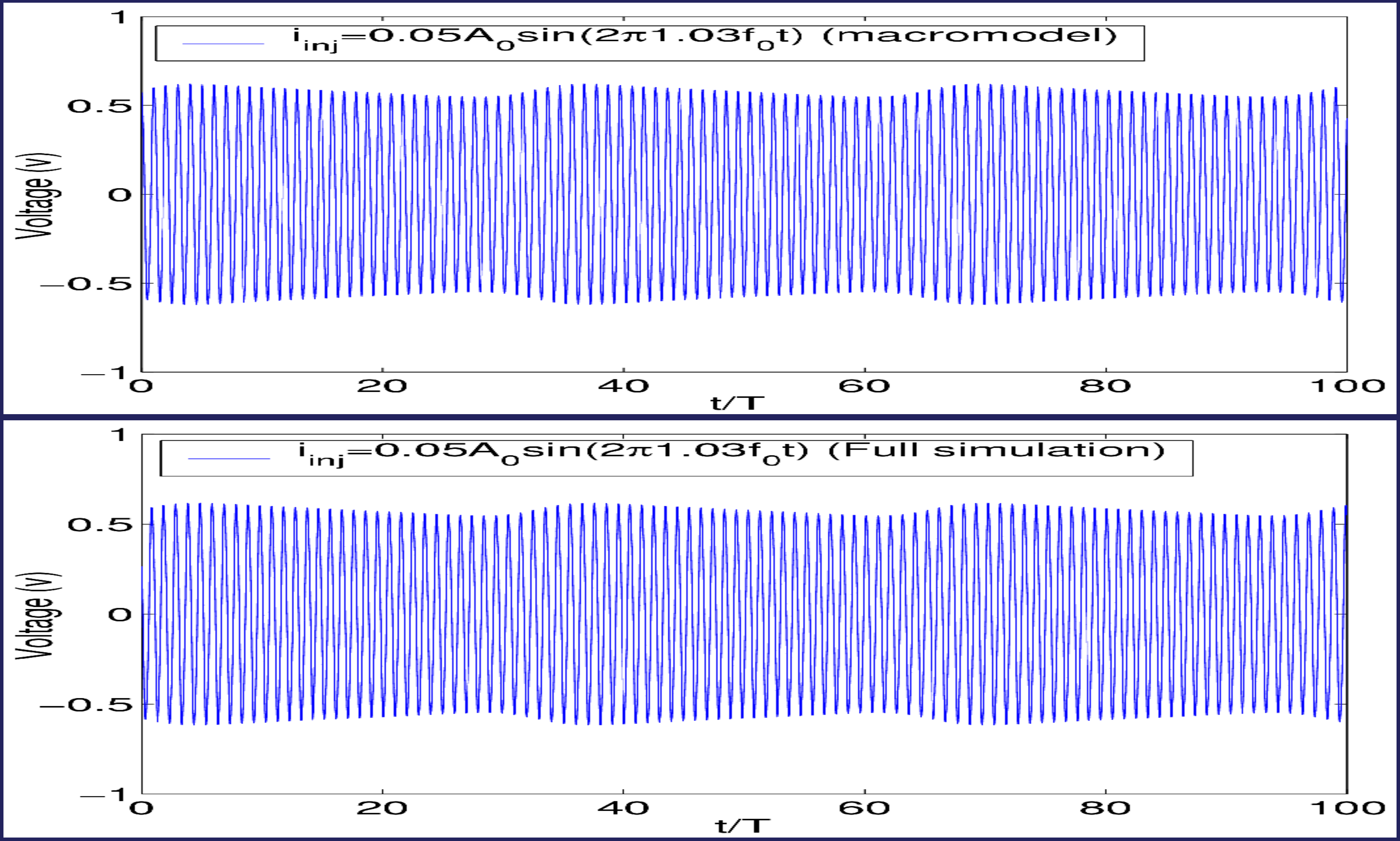
Colpitts oscillator

Full simulation vs macromodel

- ***89x speedup over original***

Capturing Amplitude Changes

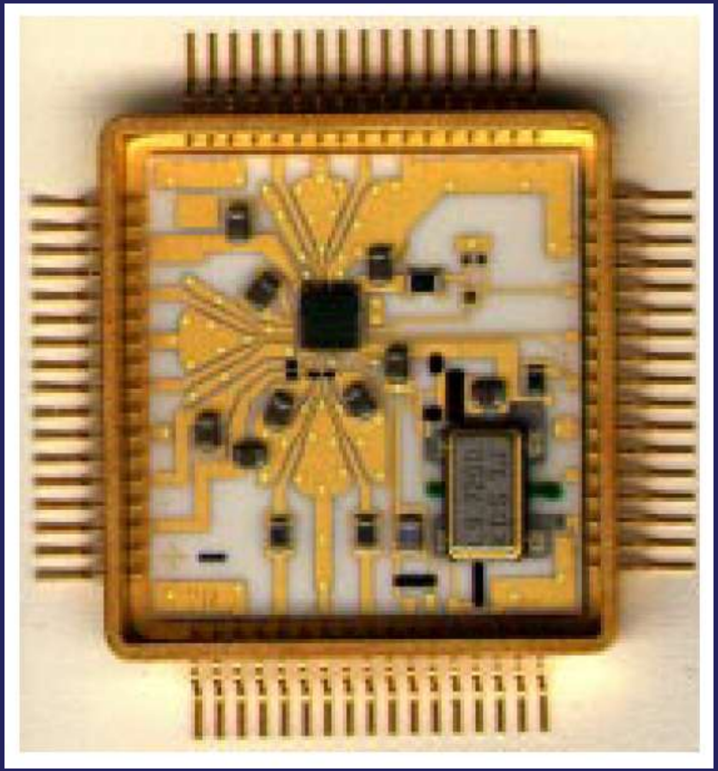
- ***nonlinear phase + amplitude components (via LTV reduction)***



PLLs: Commodity, High-Margin

Rick Walker, HP/Agilent

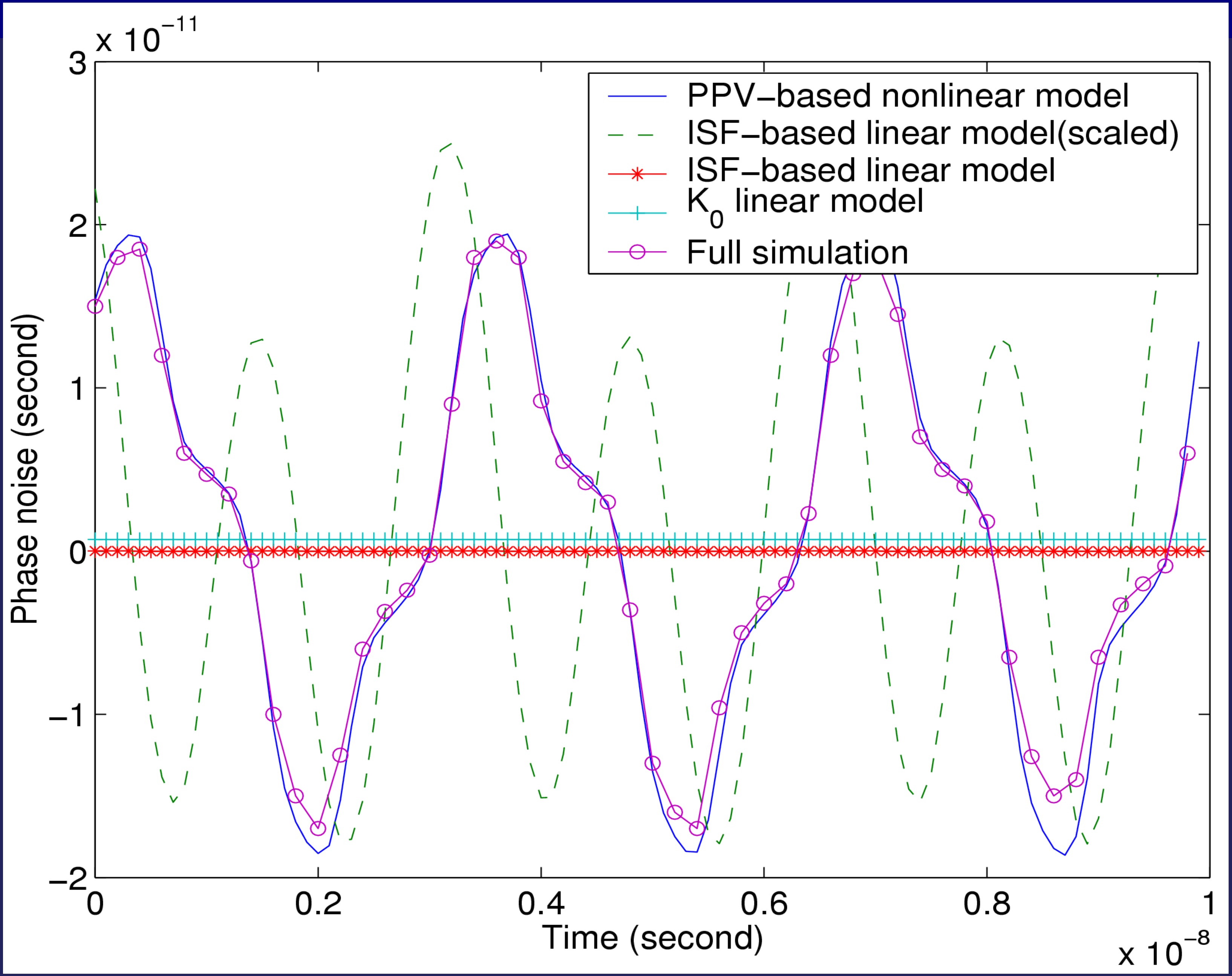
1.25Gbps Ethernet xcvr
<< $10



Rick Walker, HP/Agilent

2.44Gbps SONET CDR
$500

PLL Phase Response to Periodic Supply Noise



Conclusion

- Coming “soon”: automated nonlinear macromodelling for…
  – op-amps, mixers, switching filters, comparators
  – oscillators, VCOs (any kind: LC/ring/relaxation/etc)
  – large digital aggressor blocks: interference macromodels
  – bottom-up “extracted” macromodels: much more accurate, second-order effects, …
- Use of core macromodels for system simulation
  – ADCs/DACs/Sigma-Deltas
  – PLLs/Sigma-Deltas (incl jitter and noise)
  – SOCs
  – MATLAB/Simulink/Verilog-A/VHDL-AMS/etc
- Automated Macromodelling: the ONLY sustainable methodology for effective CAD support of nano-era analog, mixed-signal and RF design