PV-PPV: Parameter Variability Aware, Automatically Extracted, Nonlinear Time-Shifted Oscillator Macromodels

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Outline

- Parameter Variations and their Impact
  - Difficulties of Variability Simulation
- Oscillators
  - Simulation of Oscillators
- Variability Simulation of Oscillators
  - Our contribution: ***Parameterized PPV Macromodels (PV-PPV)***
- Validation

Parameter Variations and their Impact

Impact of Process Variations

Shekhar Borkar, Circuit Research Lab, Intel

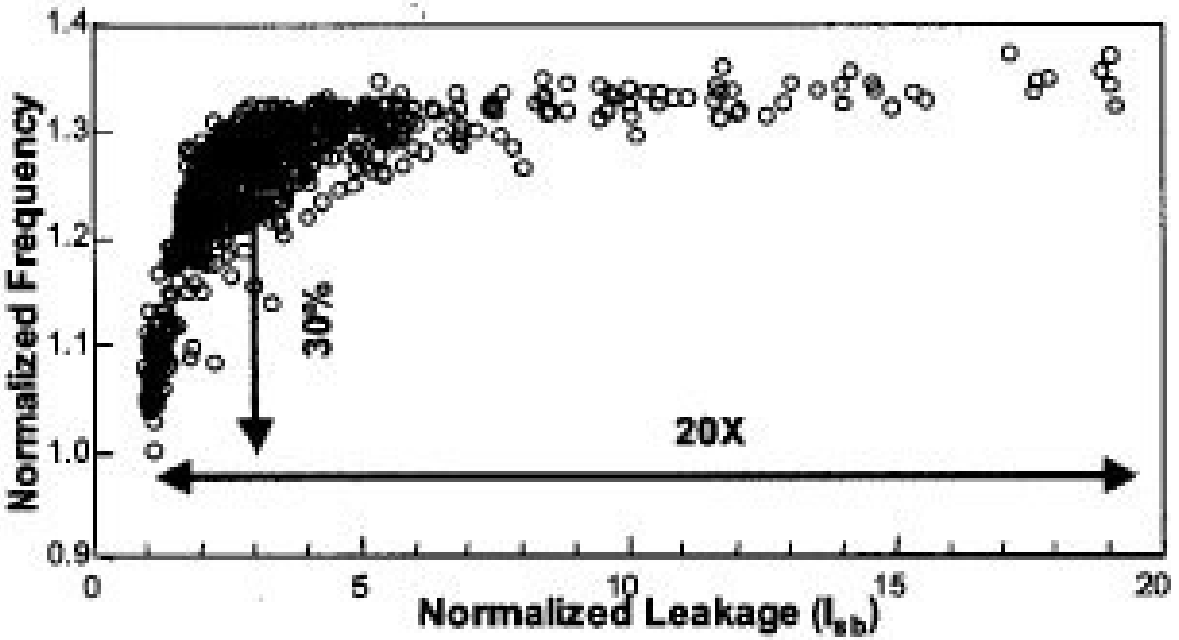

Figure 1: Leakage and frequency variations

180nm CMOS technology

- 20x variation in chip leakage
- 30% variation in chip freq

Affects yield

Distribution of frequency and standby leakage current of microprocessors in a wafer

Typical Parameters of Interest

- Supply voltage variations
  - Depend on, e.g., supply network parasitics
    - inductance, capacitance, resistance
  - Impact: e.g., 10% VDD variation causes ***20% delay***
- Temperature variations
  - Dynamic variation
  - Direct impact on ***max reliable frequency***

Parameter Variability Analysis is a MUST
in Circuit and Microarchitecture Design

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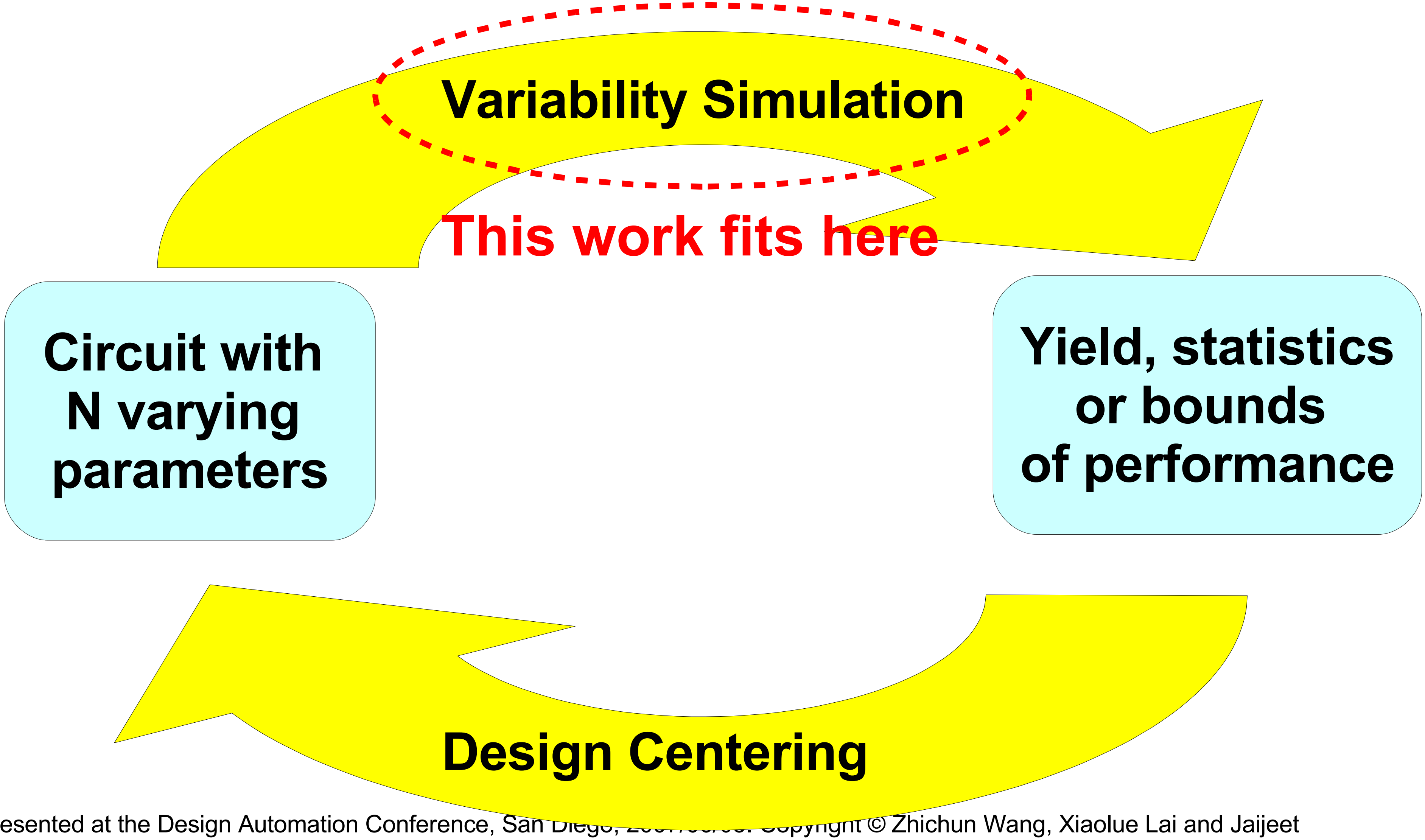
Need for Variability Simulation



Variability Simulation

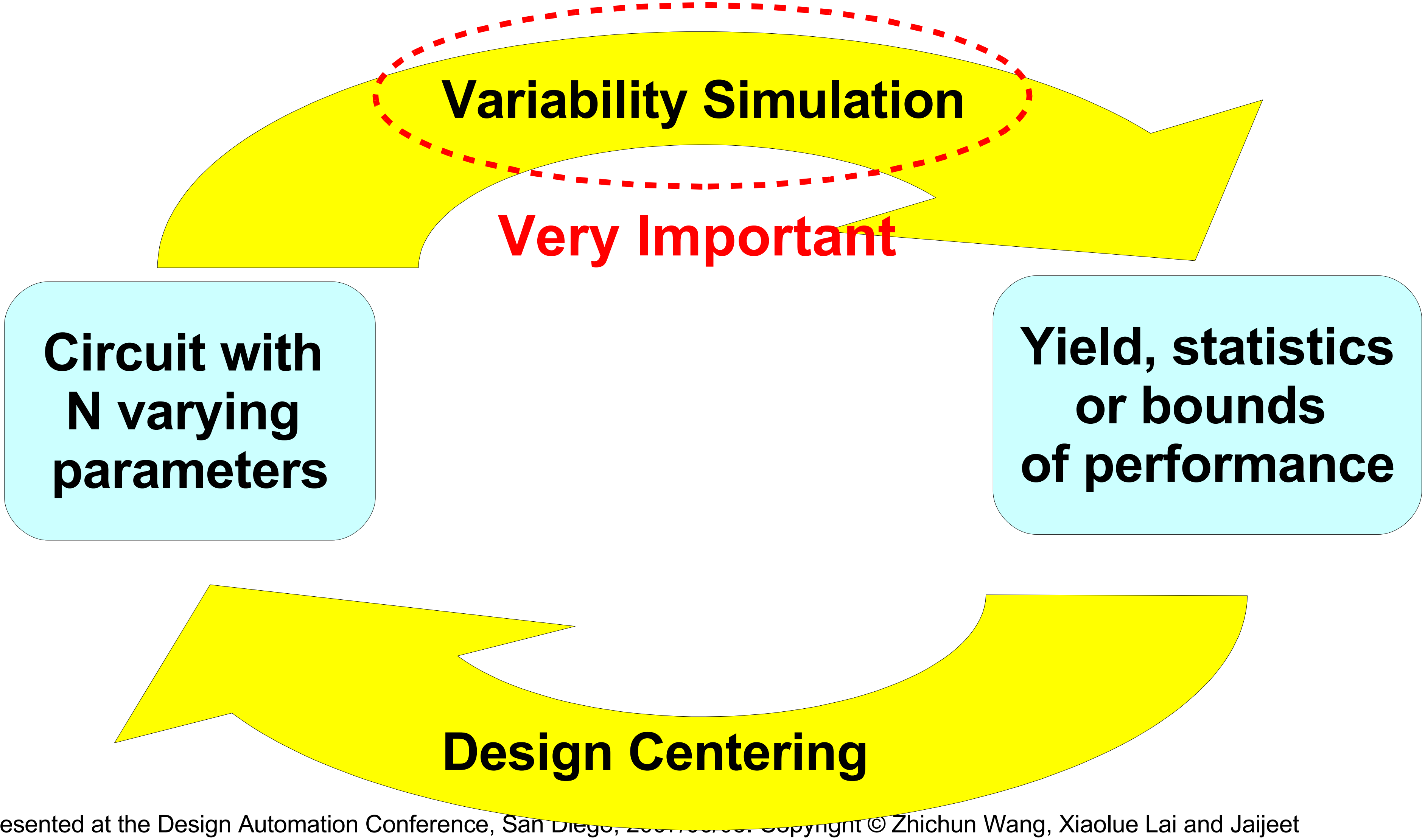
This work fits here

Circuit with N varying parameters

Yield, statistics or bounds of performance

Design Centering

Parameter Variability Simulation can be ***EXPENSIVE***



Variability Simulation

Very Important

Circuit with N varying parameters

Yield, statistics or bounds of performance

Design Centering

Parameter Variability Simulation can be ***EXPENSIVE***

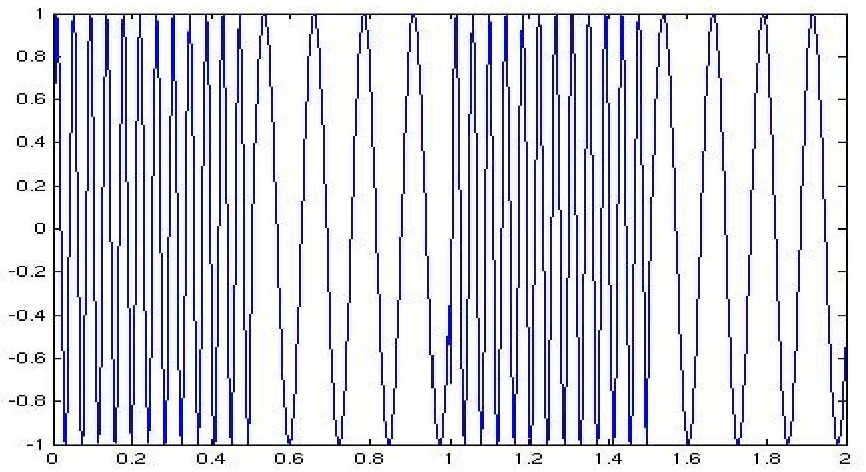
Involves thousands of simulations!

- Worst-case corner analysis samples combinations of parameters
- The number of combinations is huge
  - e.g., 2^N for min/max bounds

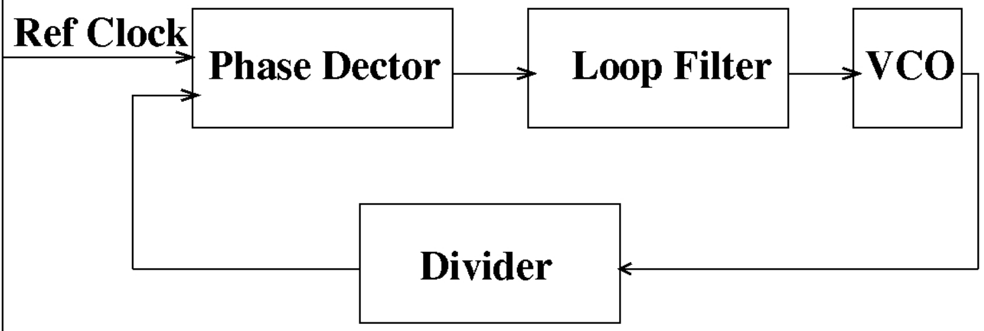
Oscillators

Oscillators in Electronic Systems

Signal carriers in communication systems



VCOs,
frequency dividers,
PLLs for mixed-signal,
high-speed digital, etc.



Phase-locked loop

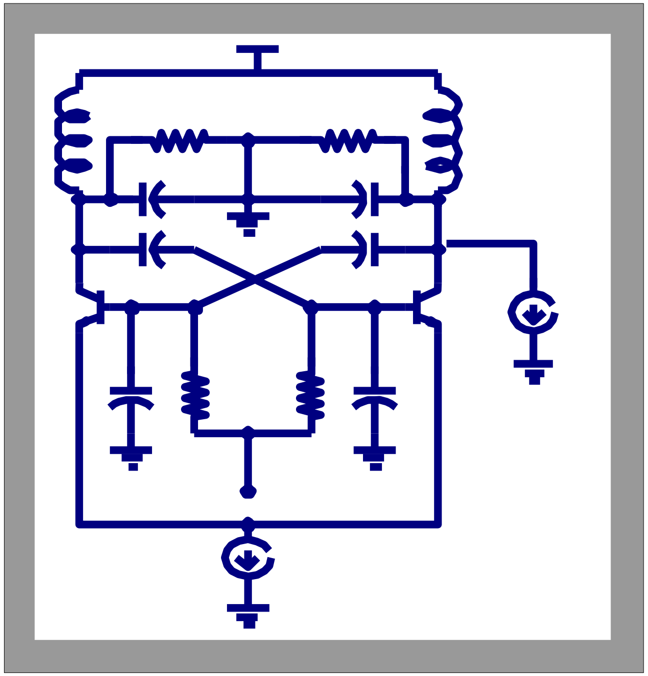
Oscillator: A Special Simulation Challenge

SPICE-based transient simulation

- **Computation/size/accuracy**: much greater than for amps/mixers
  - fundamental property of all oscillators
    - *numerical errors in phase* ***keep increasing***
    - tiny timesteps needed per cycle
  - inefficient for even 1-transistor oscillators
    - long startups: many cycles
  - integrated RF: 100s to 1000s of transistors

SPICE-based transient simulation of oscillators is not a good idea

Oscillator Macromodels

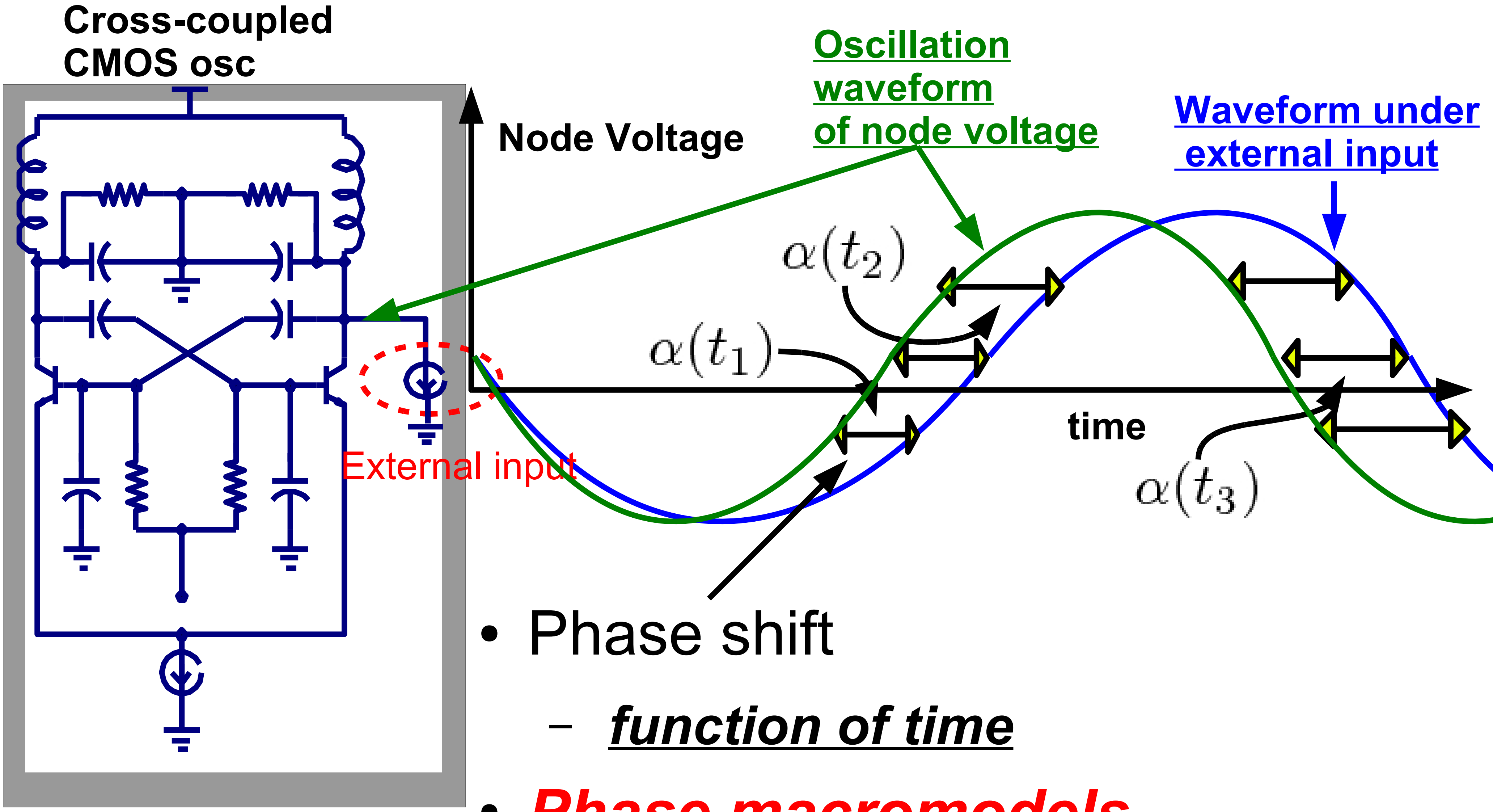


Abstraction (manual/ automated)

- Small system or circuit
  - ***fewer*** equations
  - ***much easier*** to solve

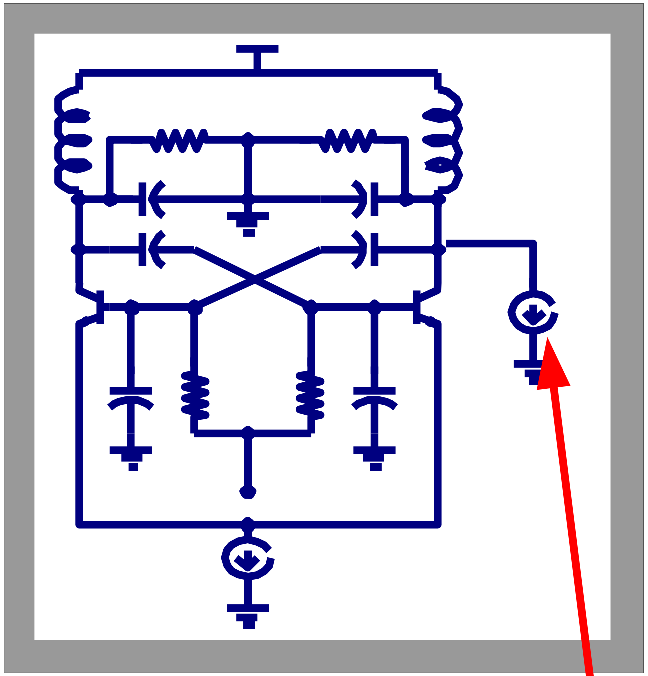
- Macromodels need to be appropriate for:
  - nature of circuit (e.g., oscillator)
  - which performance is of interest (e.g., phase, amplitude)
- In oscillators, ***phase*** ***is of key interest***

Phase Shifts in Oscillators



- Phase shift
  - ***function of time***
- ***Phase macromodels***
  - ***directly solve for phase shifts***

Oscillator PPV Phase Macromodels



$$\dot{\vec{x}}(t) + \vec{f}(\vec{x}(t)) = \vec{b}(t)$$

node voltages, branch currents

Efficient automated extraction

Oscillator PPV phase macromodels

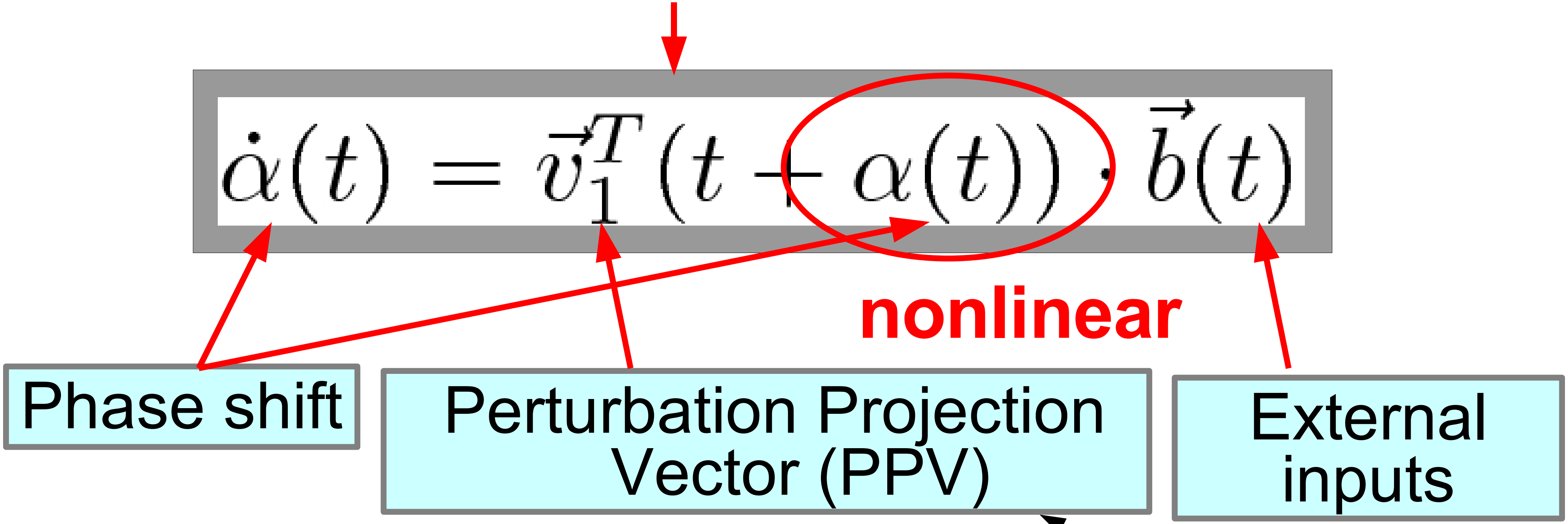
$$\dot{\alpha}(t) = \vec{v}_1^T(t+\alpha(t))\cdot\vec{b}(t)$$

large system, many equations

scalar equation

The PPV Phase Macromodels

Single scalar differential equation



$$\dot{\alpha}(t) = \vec{v}_1^T(t+\alpha(t))\cdot\vec{b}(t)$$

nonlinear

Phase shift

Perturbation Projection Vector (PPV)

External inputs

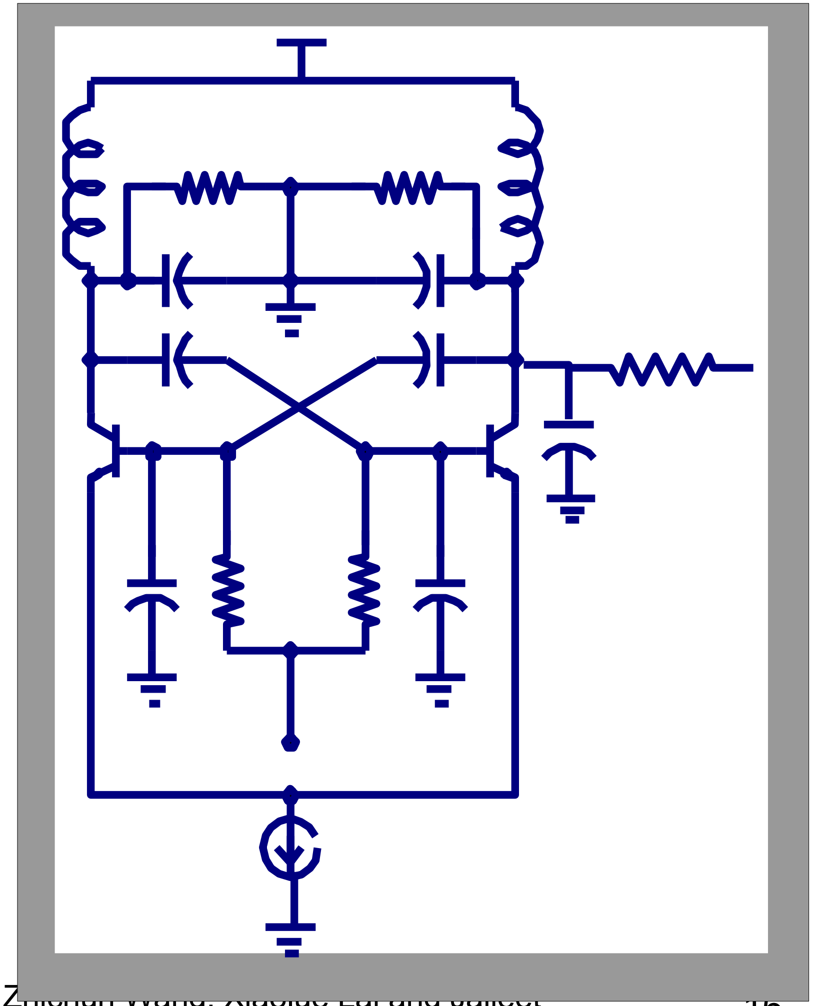
- ***Speedup: 100x to 1000x*** or more ov transient simulation

automated extracted

depends on circuits and applications

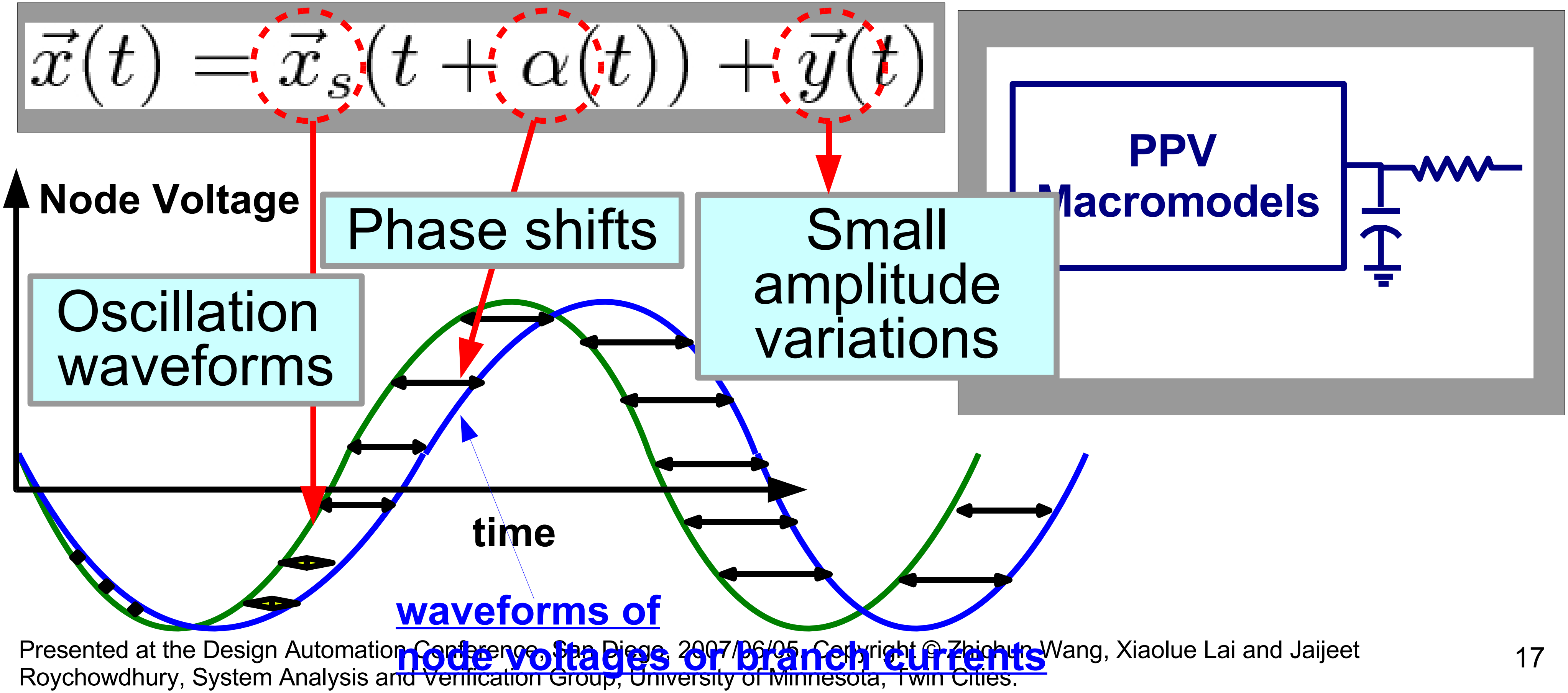
How PPV Macromodels are Used

- Replace oscillator with PPV macromodels



How PPV Macromodels are Used

- Replace oscillator with PPV macromodels
  - phase calculated by the PPV macromodel
  - waveforms of node voltages or branch currents



$$\vec{x}(t) = \vec{x}_s(t+\alpha(t)) + \vec{y}(t)$$

Oscillation waveforms

Phase shifts

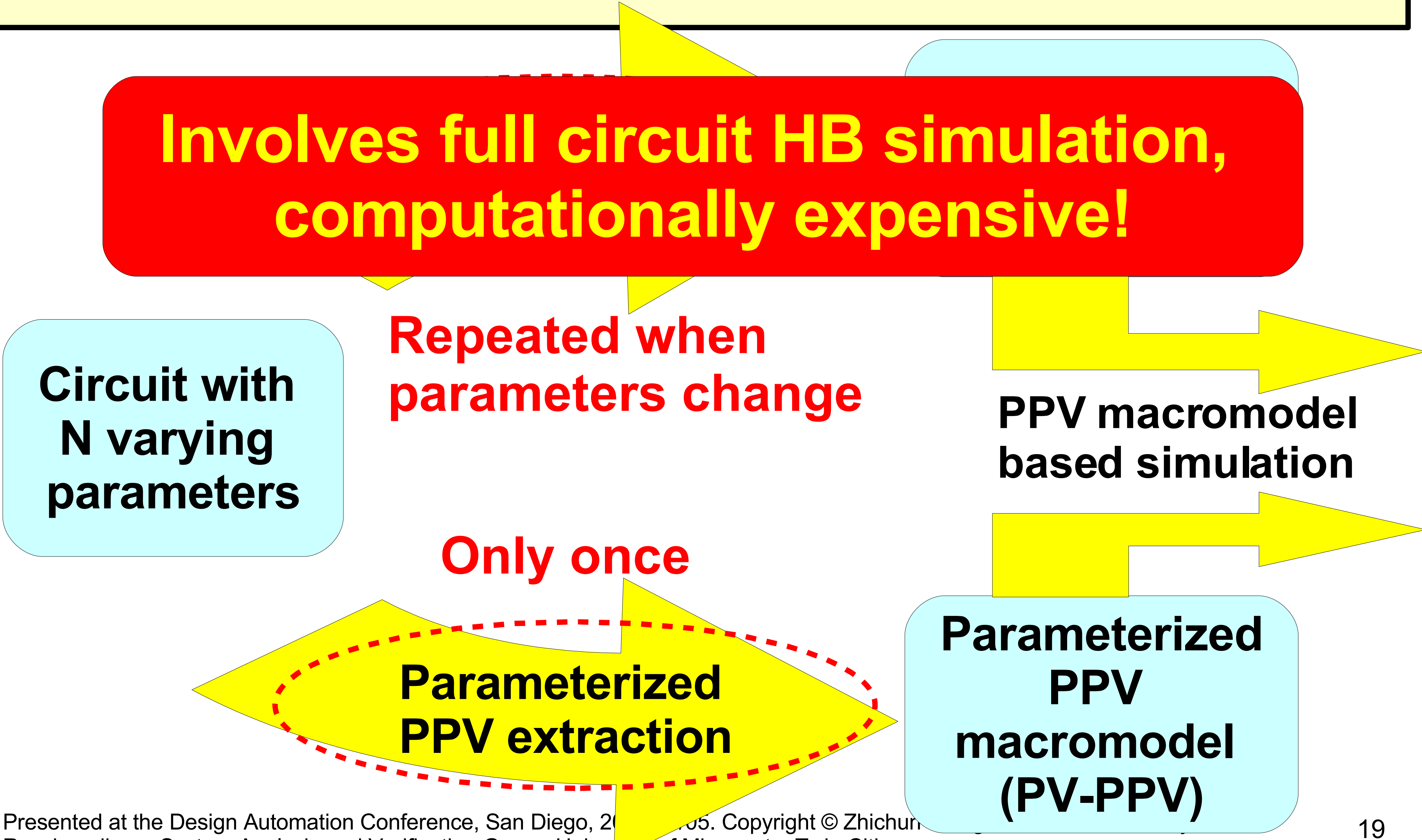
Small amplitude variations

PPV Macromodels

waveforms of node voltages or branch currents

Variability Simulation of Oscillators

Variability Simulation using PPV Macromodels



Involves full circuit HB simulation, computationally expensive!

Circuit with N varying parameters

Repeated when parameters change

PPV macromodel based simulation

Only once

Parameterized PPV extraction

Parameterized PPV macromodel (PV-PPV)

PV-PPV: Parameterized PPV Macromodels

ODE with both Perturbation and Parameter Variation

$$\dot{\vec{x}}(t) + \vec{f}(\vec{x}(t), \vec{p}^* + \Delta\vec{p}) = \vec{b}(t)$$

Parametrized PPV Macromodels

$$\dot{\alpha}(t) = \vec{v}_1^T(t+\alpha(t)) \cdot (\vec{b}(t) - \mathbb{S}_p(t+\alpha(t))\Delta\vec{p})$$

- Also solve for the phase shift

PV-PPV: Parameterized PPV Macromodels (cont.)

$$\dot{\alpha}(t) = \vec{v}_1^T(t+\alpha(t)) \cdot (\vec{b}(t) - \mathbb{S}_p(t+\alpha(t))\Delta\vec{p})$$

$$\mathbb{S}_p(t) = \frac{\partial \vec{f}(\vec{x}(t),\vec{p})}{\partial \vec{p}} \Big|_{\vec{x}_s(t),\vec{p}^*}$$

New term for variability: like a time-varying input

- Captures ***nonlinearity*** with respect to parameter variations
- Extra computation ***is trivial***

Changed for different parameter set

PV-PPV: Advantages and Limitations

- Advantages:
  - ***Avoids re-extraction*** of PPV macromodels when parameters change
    - especially useful for circuits with ***many coupled oscillators*** (e.g., high-speed serialized I/O: HyperTransport, PCI Express)
  - **Don't need original circuit** for parameter variability simulation
    - for **intellectual property (IP) protection**
- Limitations:
  - Linearization used: only applies to small parameter variations
    - but good enough for most applications

Validation

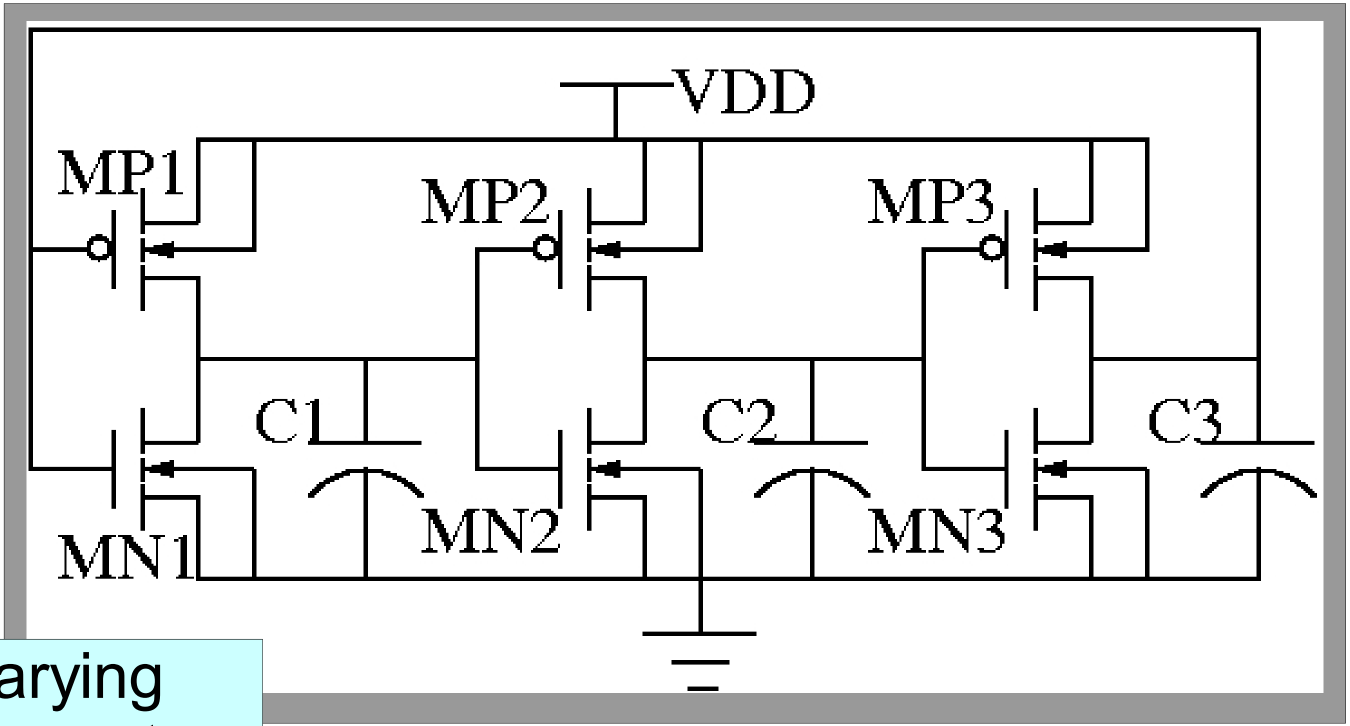
Validation Metrics

- Oscillator frequency changes due to parameter changes (no external input)
  - validate accuracy, speedups (compared to repeated extraction via HB)
- System application: many coupled oscillators
  - **network of 40,000 coupled oscillators** with randomly varying parameters

Speedups for Calculating Center Frequency Shifts (compared to HB)

- Using HB simulation
  - many HB simulations: one per parameter set (**time consuming**)
- Using PV-PPV
  - only one HB simulation: at nominal parameter values (**expense of repeated HB avoided**)
  - one extraction: PV-PPV macromodel (***efficient***)
  - one PPV-based transient simulation per parameter set (***scalar equation, very fast***)
- Speedups depend on number of parameter sets of interest for simulation

3-Stage Ring Oscillator



varying parameter

- Nominal parameters

$$v_{tn1} = v_{tn2} = v_{tn3} = v_{t0} = 0.3V$$

$$v_{tp1} = v_{tp2} = v_{tp3} = -v_{t0} = -0.3V$$

- Nominal frequency

$$f_0 = 0.906GHz$$

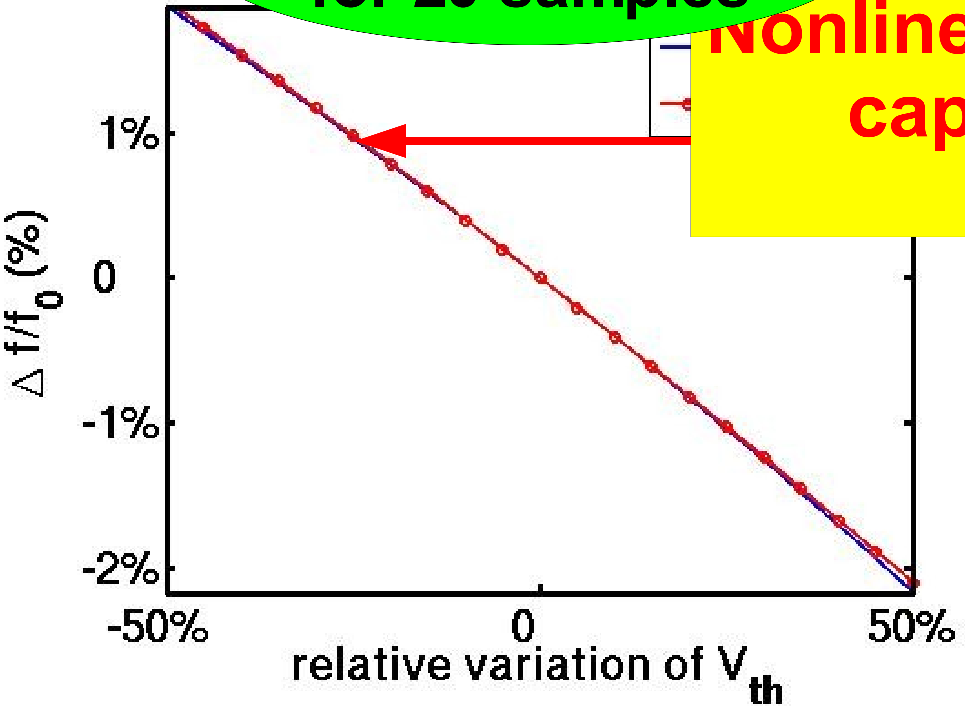
Center Frequency vs Threshold Voltage

- Relative frequency change (PV-PPV vs HB)

33.8sec

238sec

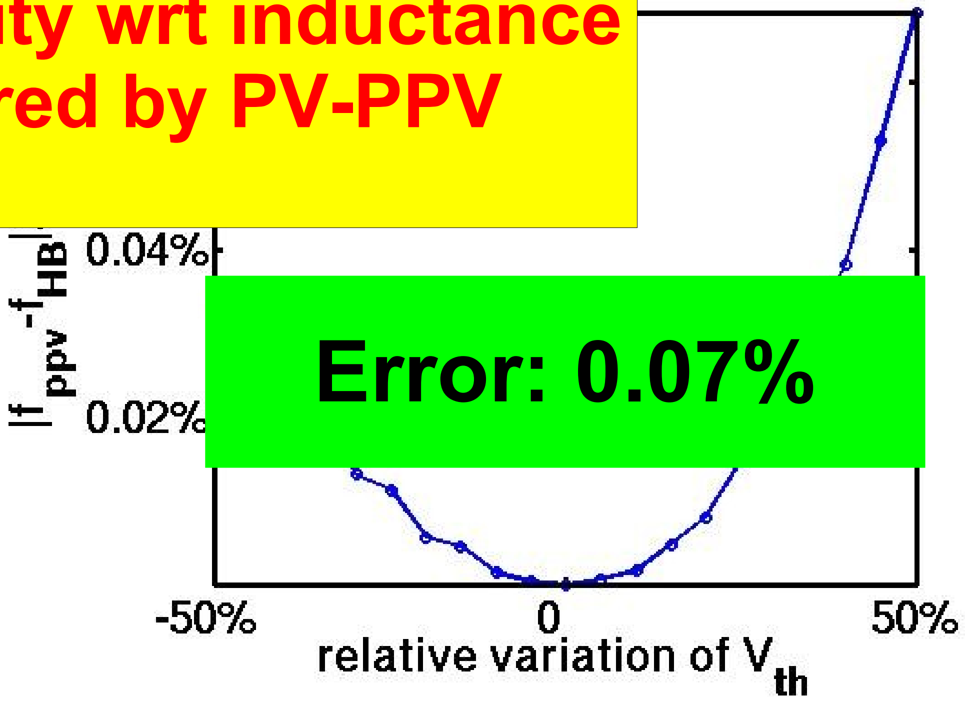
Speedup: 7.04x for 20 samples



Nonlinearity wrt inductance captured by PV-PPV

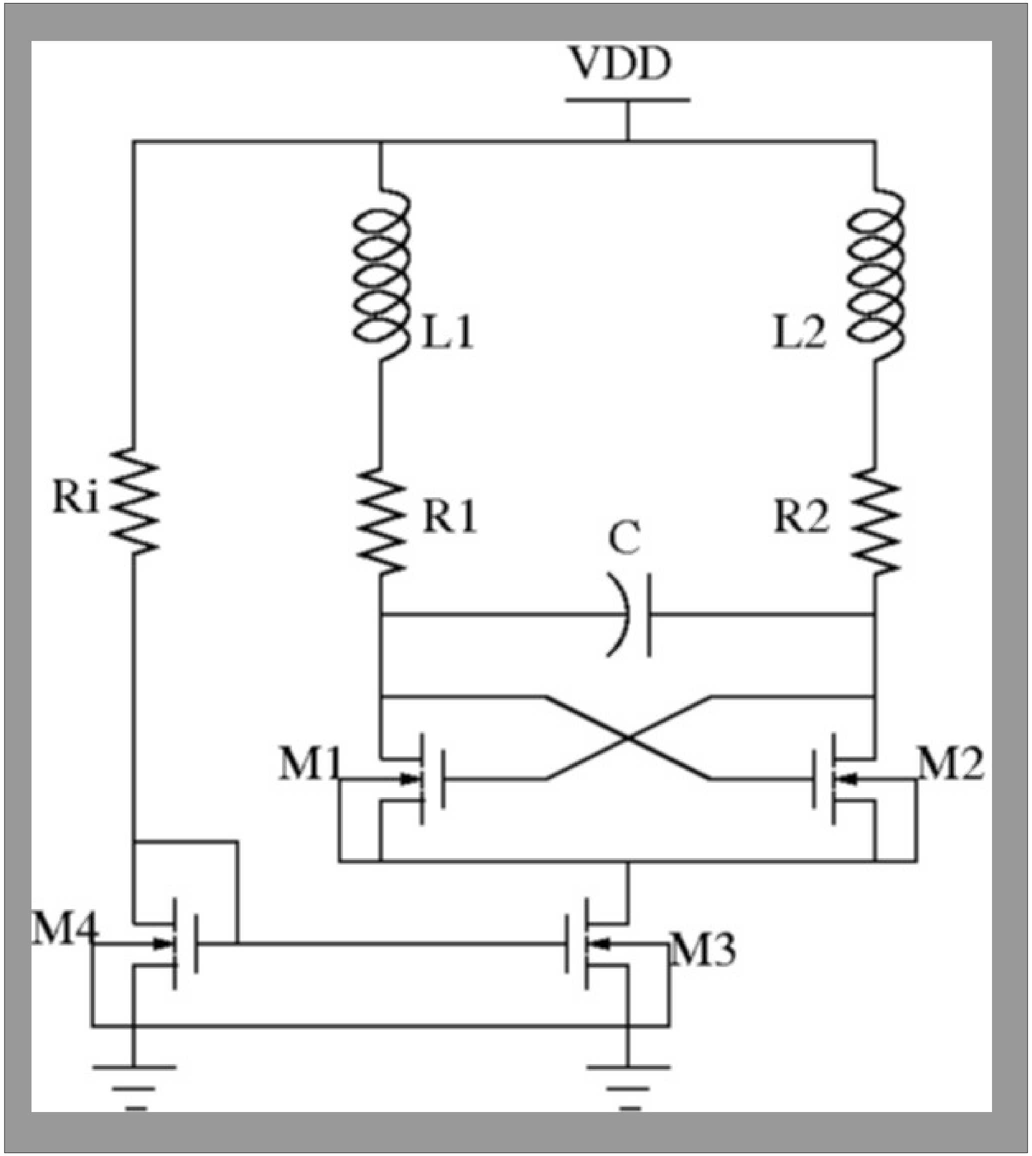
- Relative frequency error (compared to HB)

$$\frac{|f_{ppv}-f_{HB}|}{f_0}$$



Error: 0.07%

Cross-Coupled LC Oscillator



- Nominal parameters

$$L_1 = L_2 = L_0 = 38.7nH$$

$$C_0 = 318fF$$

$$Q \approx 427$$

varying parameter

- Nominal frequency

$$f_0 = 0.962GHz$$

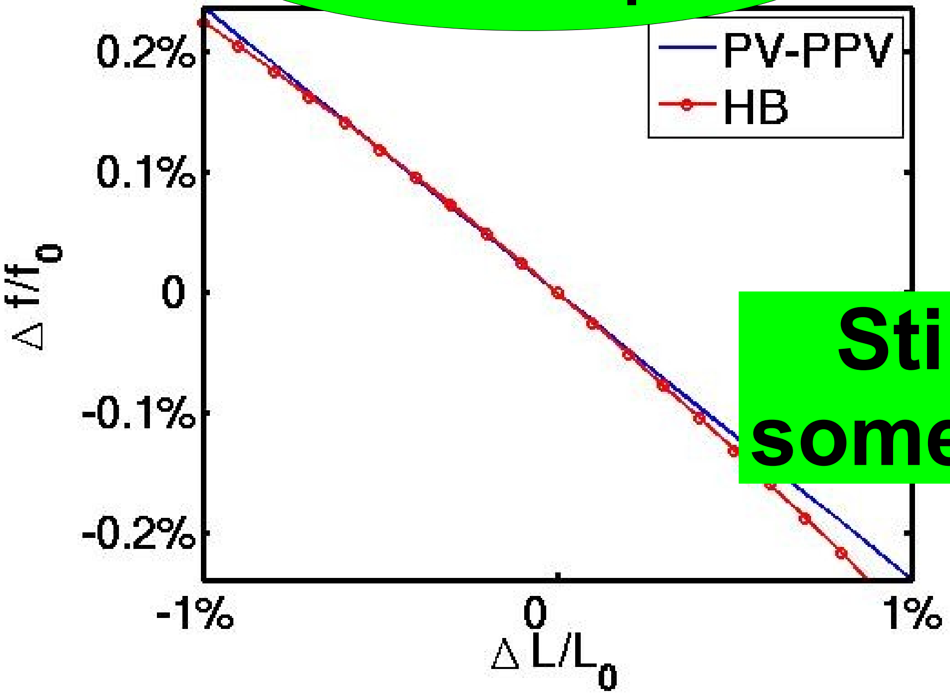
Center Frequency vs Inductance

- Relative frequency change (PV-PPV vs HB)
- Relative frequency error (compared to HB)

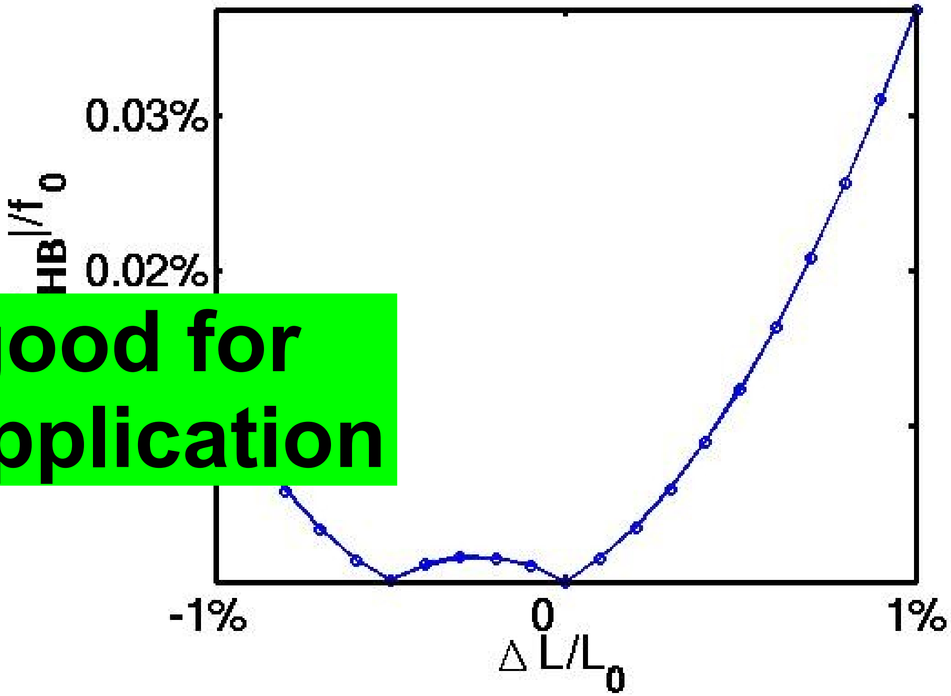
86.5sec

16.9min

Speedup: 11.7x for 20 samples

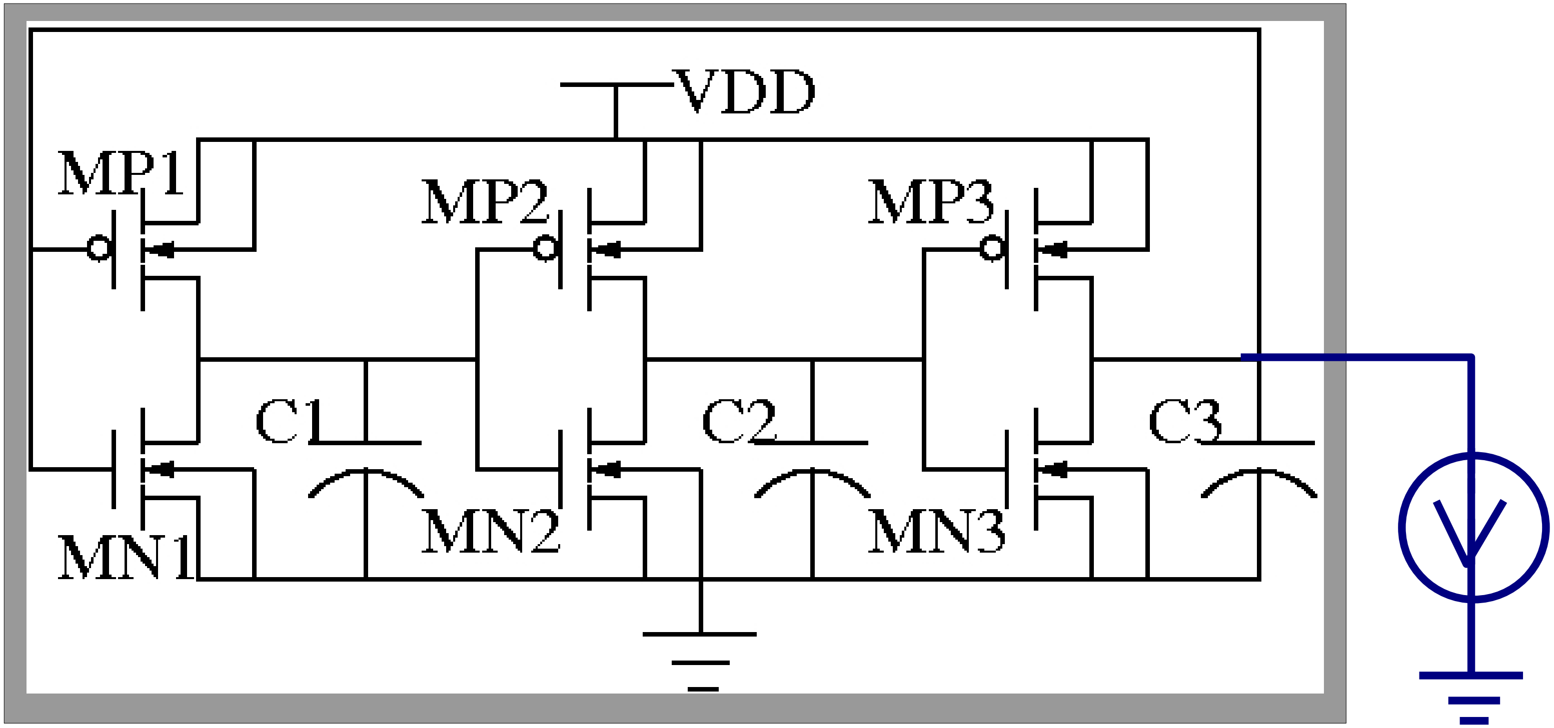


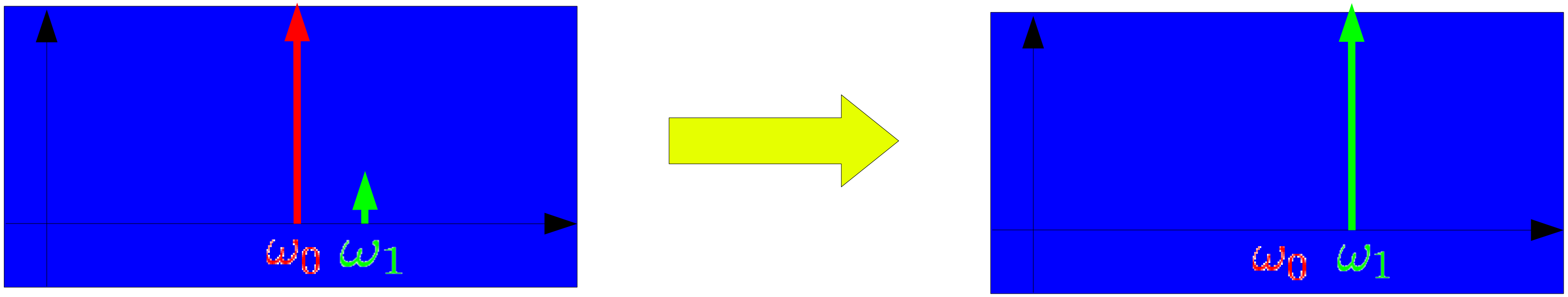
$$\frac{|f_{ppv}-f_{HB}|}{f_0}$$



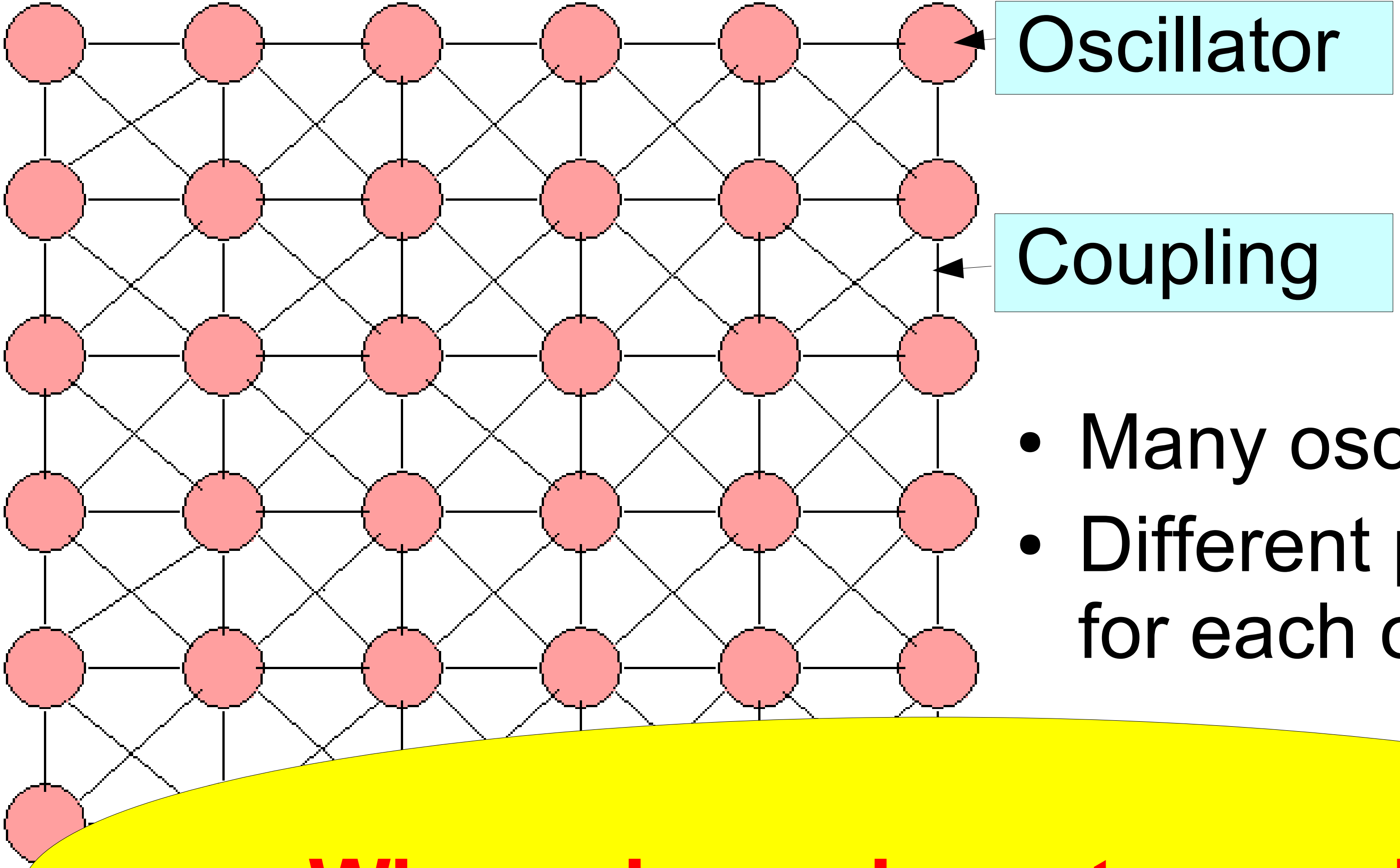
Still good for some application

Injection Locking in Oscillators





System Simulation: Many Coupled Oscillators with Varying Parameters

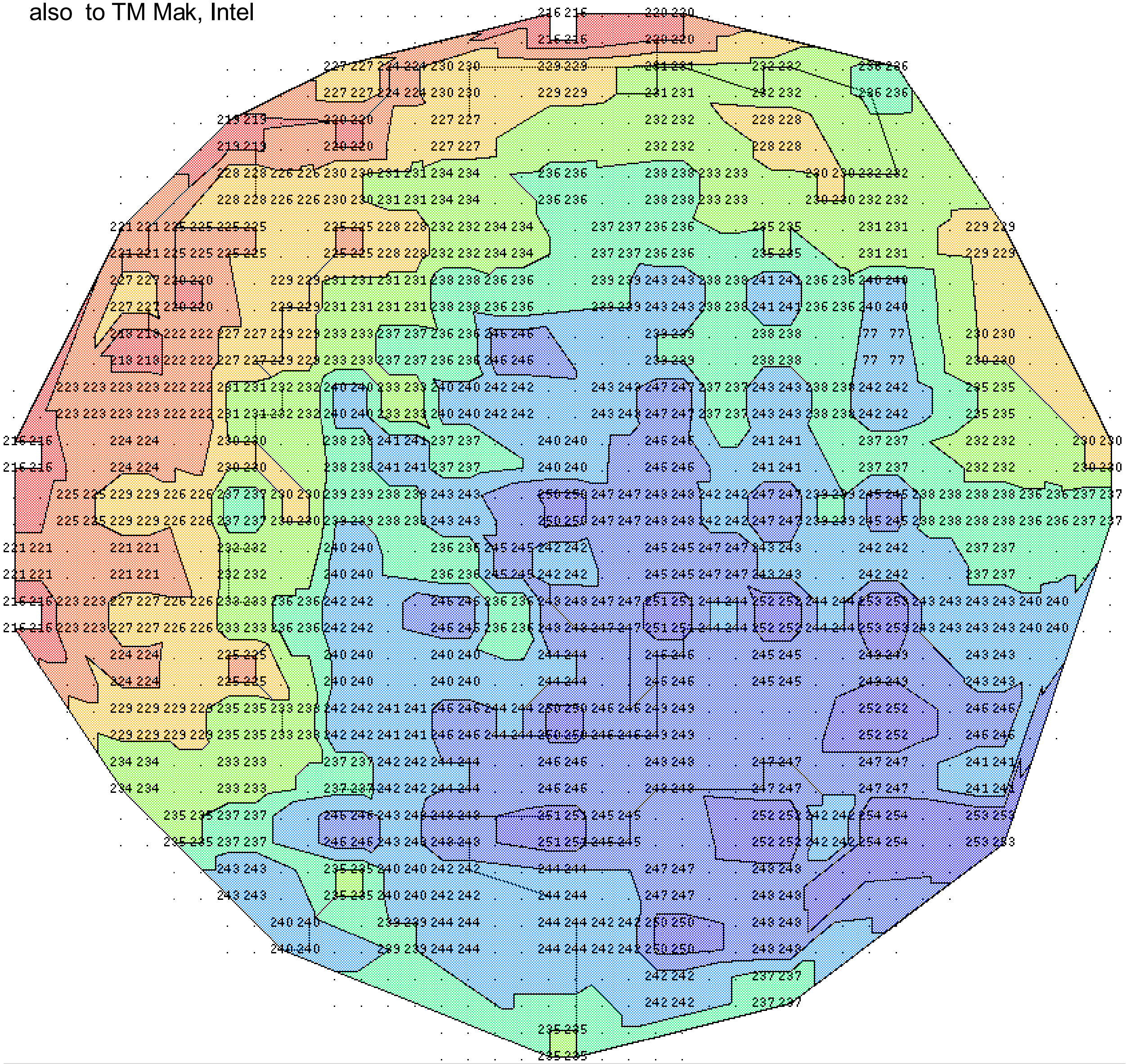


- Many oscillators
- Different parameters for each oscillator

Where do such systems arise?

Reasons for System Simulation

- Many ring oscillators on a single wafer
  - new process
  - variability measurements
  - undesired coupling
- Bio-mimetic "collaborative radio"
  - deliberately designed coupling



Courtesy Sani Nassif, IBM; thanks also to TM Mak, Intel

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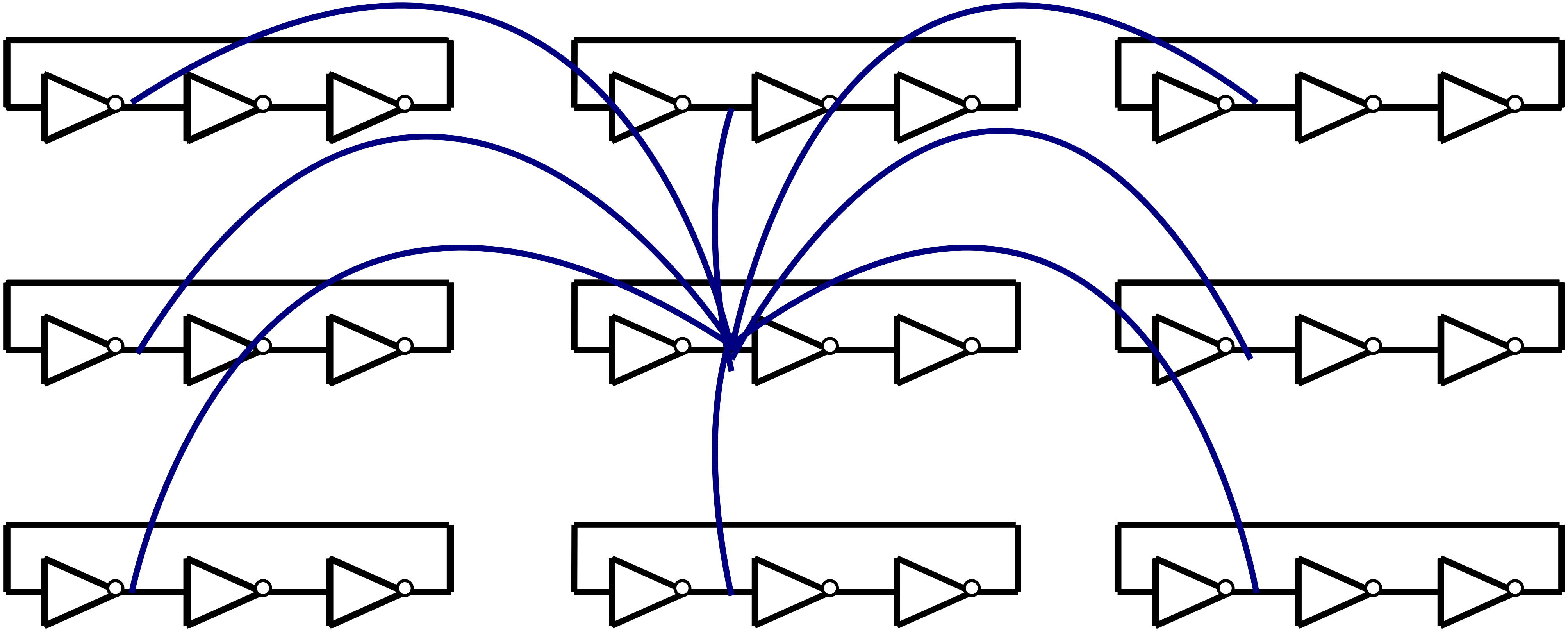
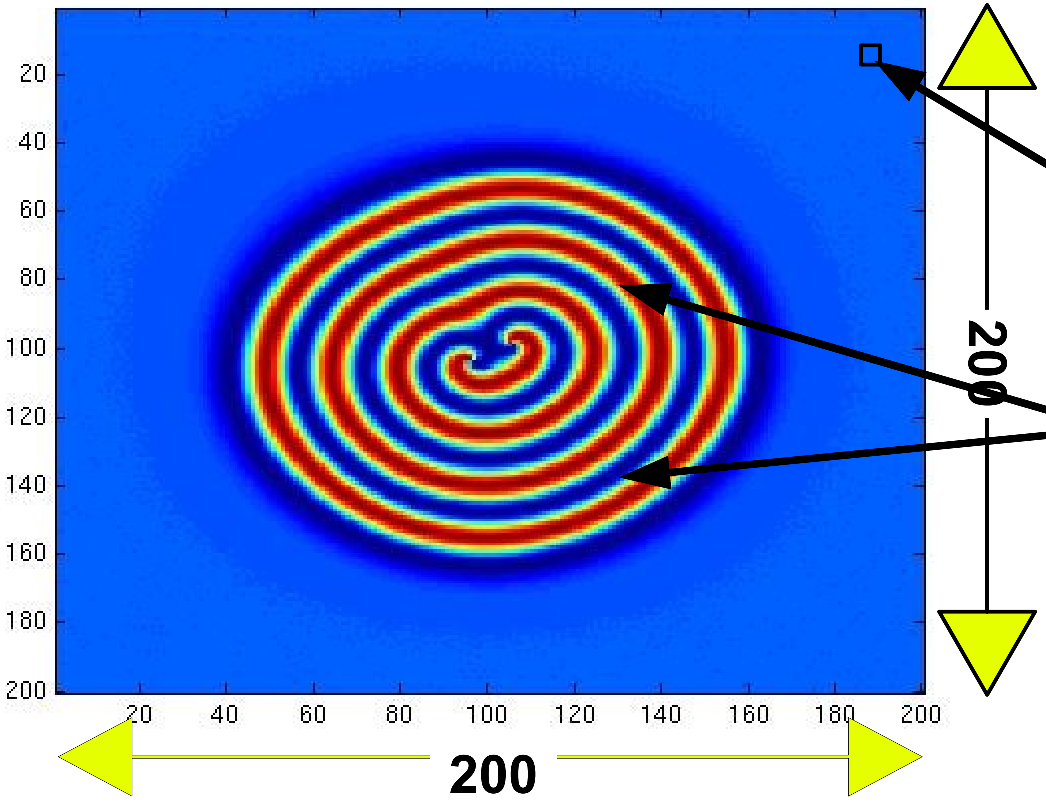
3x3 sub array



- 3-stage ring oscillator
- Each blue line: a resistor

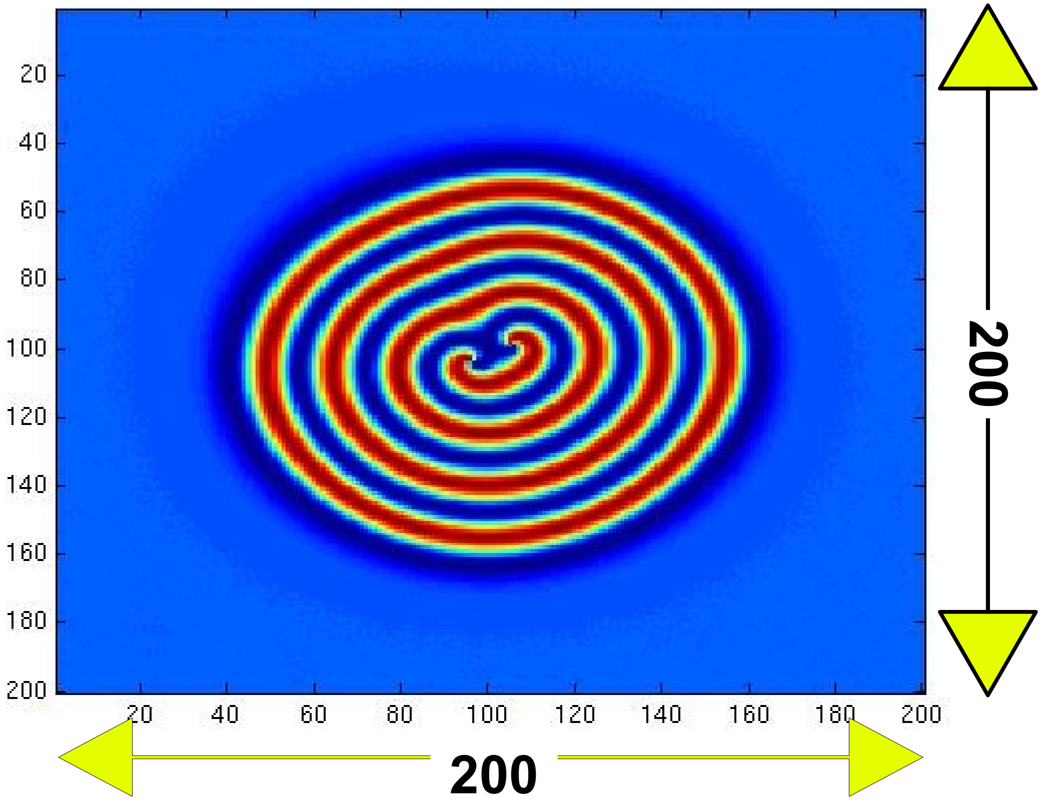
Pattern Formation in 200x200 Coupled Oscillator Network



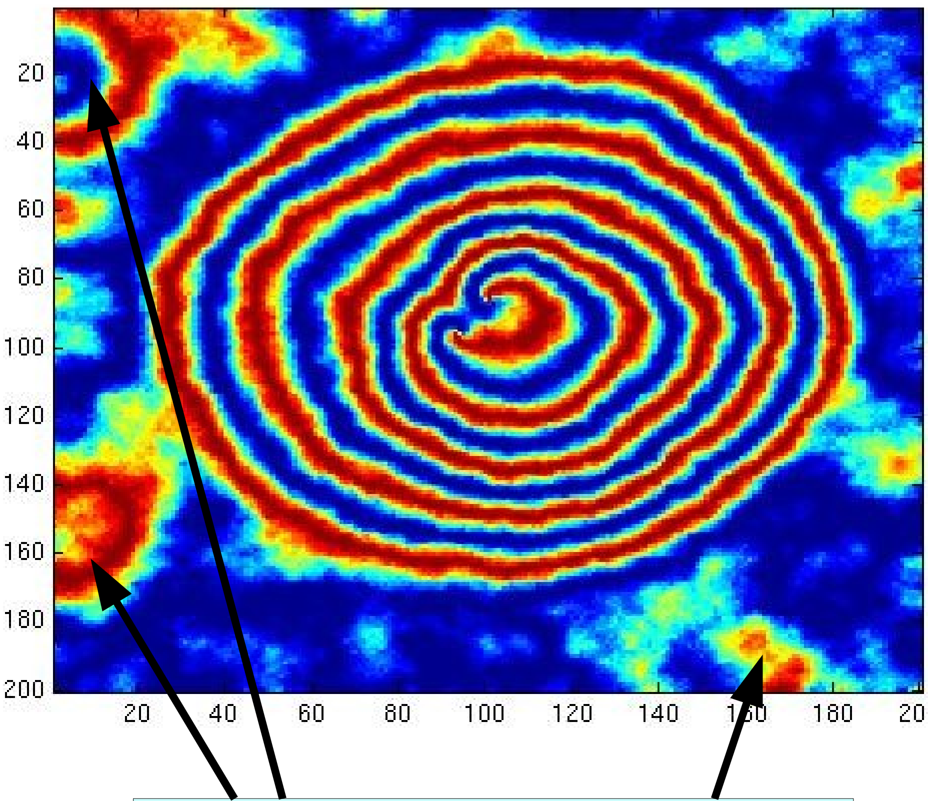
- 40000 coupled oscillators
- Each little square: an oscillator
- Color: phase of each oscillator
- Many oscillators with same phase
- Spontaneous pattern formation

Pattern Formation in 200x200 Coupled Oscillator Network

No parameter variations



Gaussianly distributed Vth



Imperfection due to parameter variations

Speedups for Simulating Networks of Many Coupled Oscillators

- 40000 coupled oscillators
  - each oscillator: 3-stage ring (BSIM3 MOS model)
- For 200x200 network of locally coupled oscillators:
  - CPU time (AMD Athlon 64 Dual Core 3800+; 1GB RAM):
    - extracting one PV-PPV macromodel: **72.7s**
    - extracting 200x200 PPV macromodels: ***3.36 days***

Speedup: 39932x

Summary

- ***Parameterized*** PPV macromodels (PV-PPV)
  - avoid ***re-extraction*** of PPV macromodels for different parameters
  - ***intellectual property*** (IP) protection
  - capture ***nonlinear effects***
- Speedups:
  - calculating frequency shifts for 20 parameters
    - ***7.04x*** (ring oscillator), ***11.7x*** (LC oscillator)
  - ***39932x*** for simulating 40000 coupled oscillators