Mixed-Level Circuit and Device Simulation

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Outline

- Introduction
- Mixed-level (coupled) circuit/device simulation
- Advantages and applications
- Simulator architecture and algorithms
- Radio frequency (RF) simulation issues
- Extensions to microsystem simulation

The Modeling Hierarchy

Speed ⟷ **Accuracy**

High-level models	Lumped-element models	Compact models	Numerical models
VHDL-AMS	**RLC**	**BSIM3**	**PISCES**

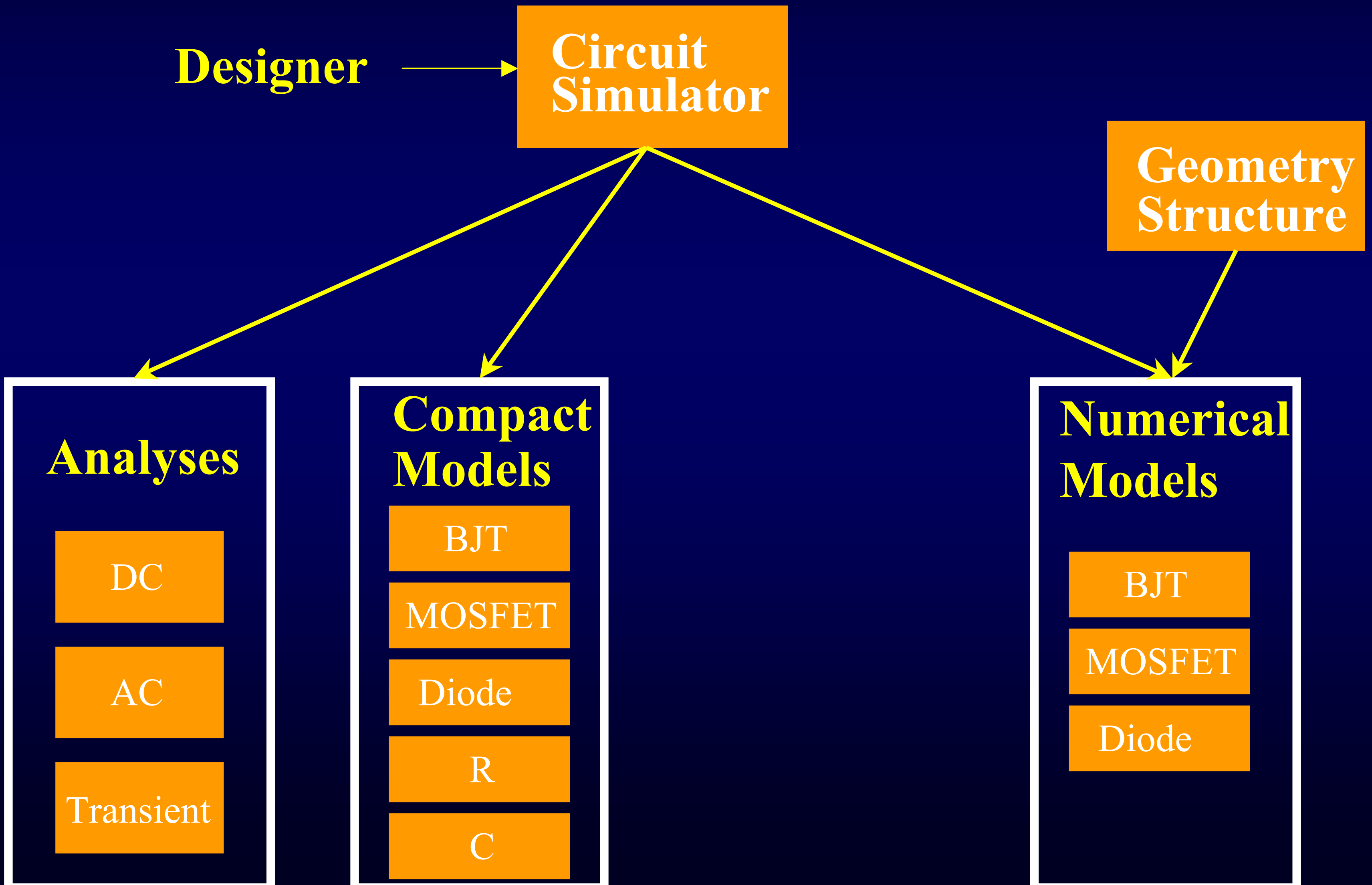
Circuit/Device Simulation

- **Circuit simulation**
  - – Analytical (compact) models used: inaccurate under certain conditions
  - + Simulation of multiple devices in a circuit
- **Device simulation**
  - + Based on device physics: accurate
  - – Simulation of a single device, no circuit embedding
- **Coupled circuit/device simulation**
  - + Accurate
  - + Simulation of complete systems

Coupled Circuit/Device Simulator

- Compact models for electronic components (BJTs, MOSFETs, …)
- Accurate numerical models for various components
- Analysis capabilities supported by the circuit simulator

Coupled Circuit/Device Simulator

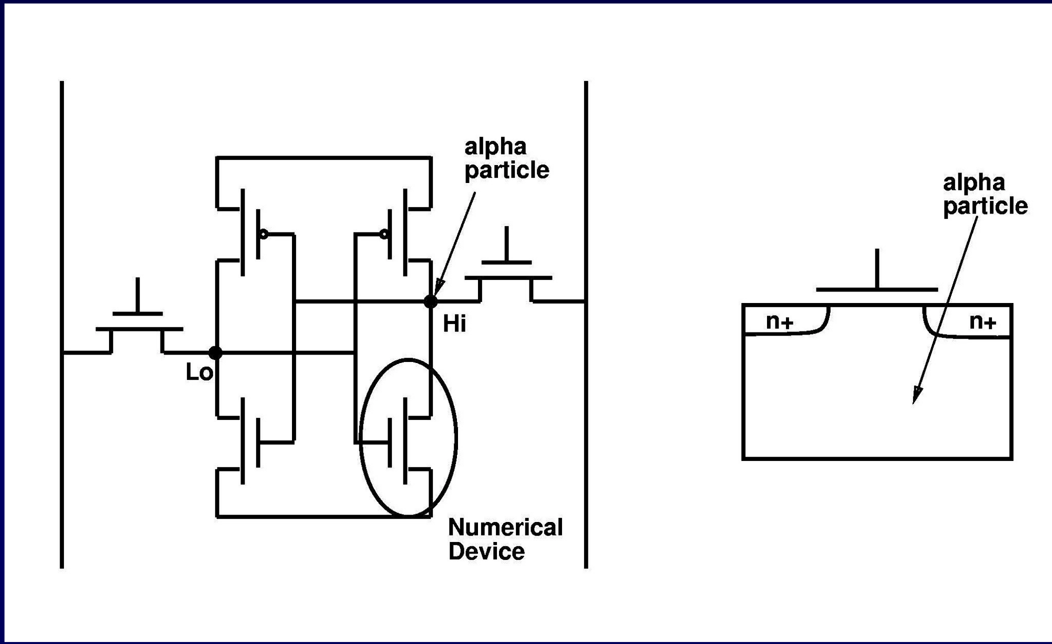


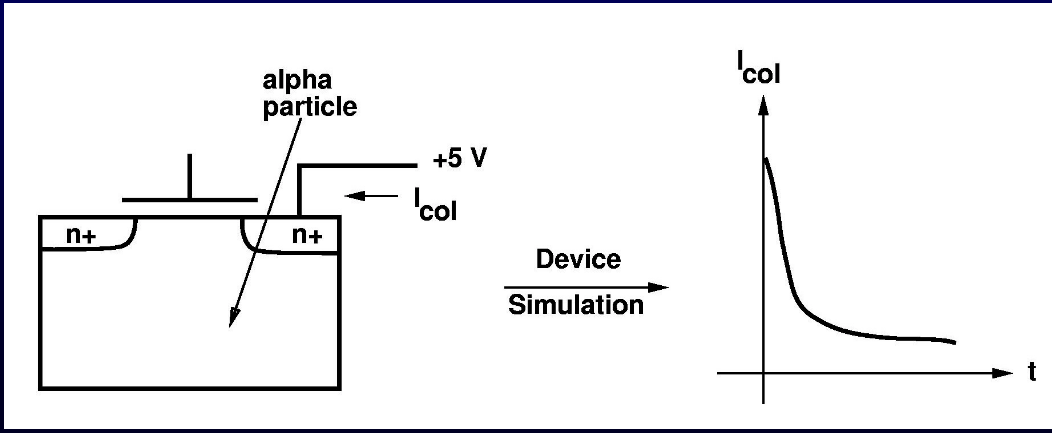
Advantages

- Simulate critical devices at the device level within a circuit
  – Solve partial differential equations describing devices coupled to a circuit simulator
- Predict performance of circuits in absence of compact models for devices
- Evaluate influence of process variations on circuit performance

Application Example – Single Event Upset in SRAM Cell

- Critical transistor modeled at the physical (numerical) level
- Other transistors modeled with compact models
- Alpha particle strike simulated with circuit boundary conditions





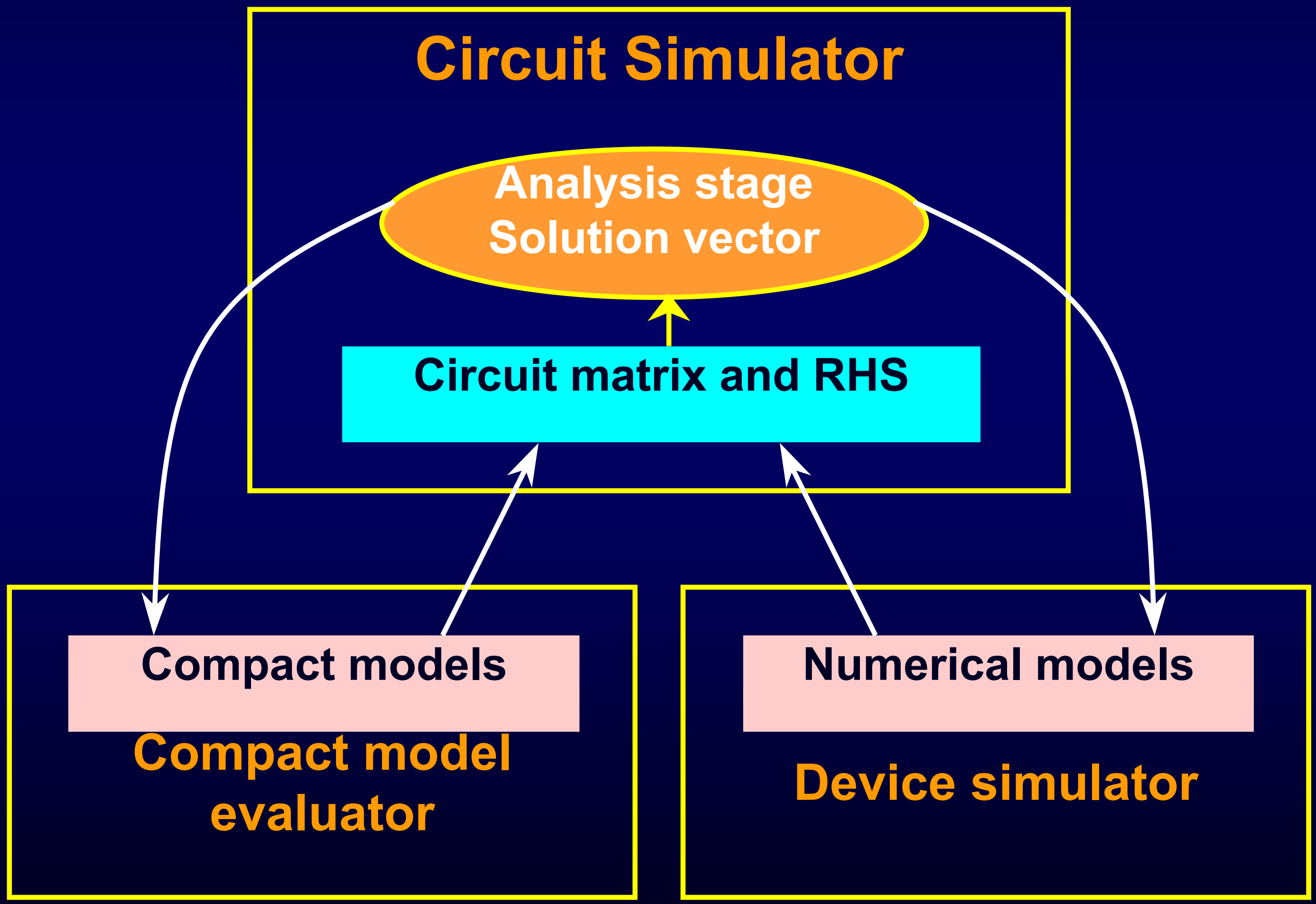
Application Examples

- Delay analysis of BiCMOS driver circuits
- Simulation of power devices
- Determination of switch-induced error in MOS switched-capacitor circuits
- Simulation of RF circuits
- Simulation of single-event-upset in SRAMs
- Validation of analytical models

Coupled Device and Circuit Simulator (CODECS)

- **Device-level simulator (PDE solver)**
  - Poisson's and current-continuity equations
  - Accurate terminal conductances and capacitances provided to circuit-level simulator
- **Circuit-level simulator (SPICE3)**
  - Compact model evaluation
  - Simulation engine

Architecture of CODECS



Equation Formulation

- **Modified nodal admittance matrix formulation for circuit equations**

$$F(x,\dot{x},t) = 0$$

x is the vector of unknown node voltages and voltage source currents

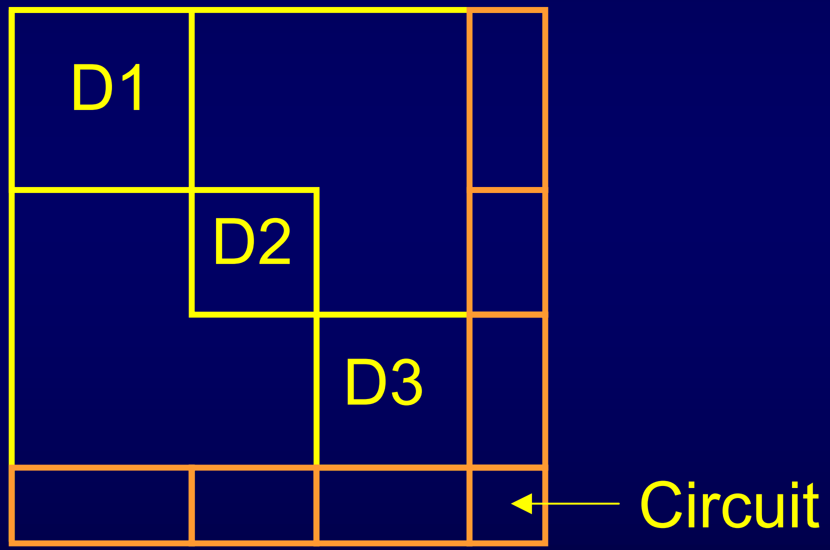
- **Device equations after space discretization can also be expressed as**

$$G(u,\dot{u},t) = 0$$

u is the vector of unknown electrostatic potential, electron and hole concentration at each grid point

Equation Solution

- With voltage boundary conditions for numerical devices and Newton's method



  - Full Newton: block LU decomposition used
  - Two-level Newton: solve devices to convergence

Various Equation Solution Methods

- **Two-level Newton**
- **Modified two-level Newton**
  - Two-level Newton with improved initial guess
- **Full Newton**
- **Block iterative algorithm**
- **Two-level Newton has better convergence but higher computational cost**
  - Use two-level Newton scheme for DC analysis
  - Use full Newton scheme for transient analysis

DC Analysis Iterations

Circuit	m2lev	2lev	full Newton	blocklt
RTLinv	8	8	8	-
Osc	8	8	9	-
VCO	8	-	10	-
Invchain	9	-	-	-
Astable	9	-	-	-
MECL	51	51	-	-

- No convergence in 100 iterations

Transient Analysis Iterations

Circuit	m2lev	2lev	full Newton	blocklt
Osc	16916	16916	18333	23836
VCO	5093	5109	5864	7028
Invchain	1563	1578	1716	2324
Astable	5930	6305	6369	9087
MECL	2450	2450	2609	3236
Cpump	1644	1661	1850	2661

RF Simulation Issues

- **Accurate and efficient steady-state simulation of RF ICs required for**
  - Distortion, power, frequency, and noise
  - Gain and impedance characteristics
- **Simulation techniques**
  - Time-domain shooting method
  - Harmonic-balance method

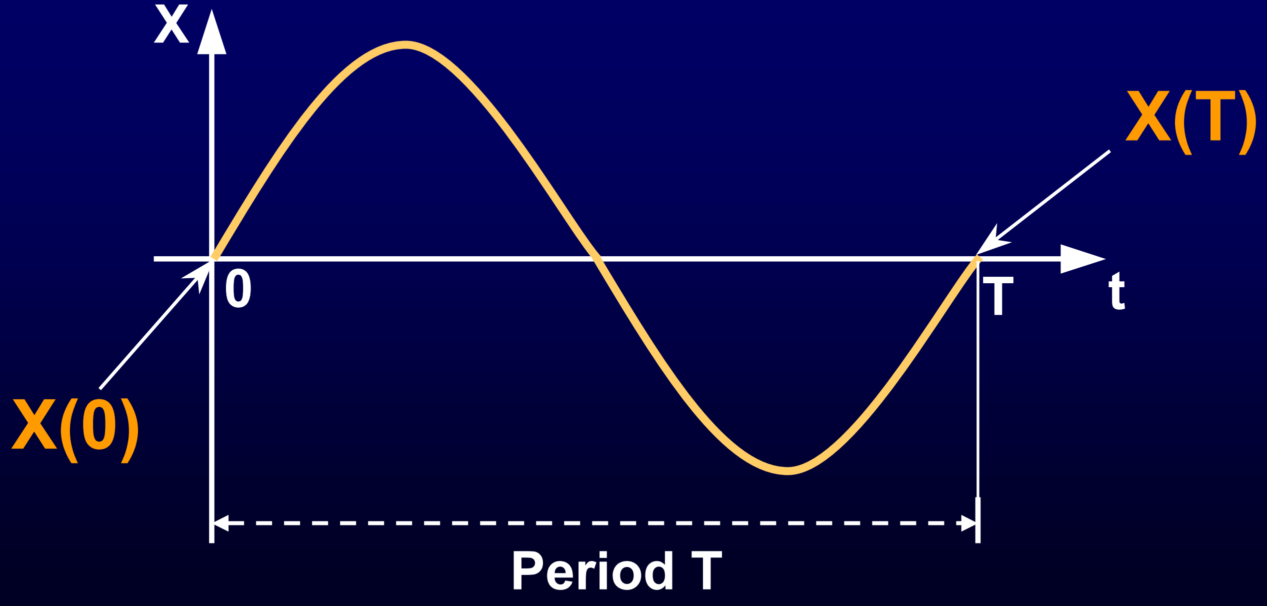
RF Simulation Issues

- **Distributed effects in devices important for RF applications**
  - Use physical models in absence of accurate compact models
    - ⇨ Coupled device and circuit simulation

Time-Domain Periodic Steady-State Analysis

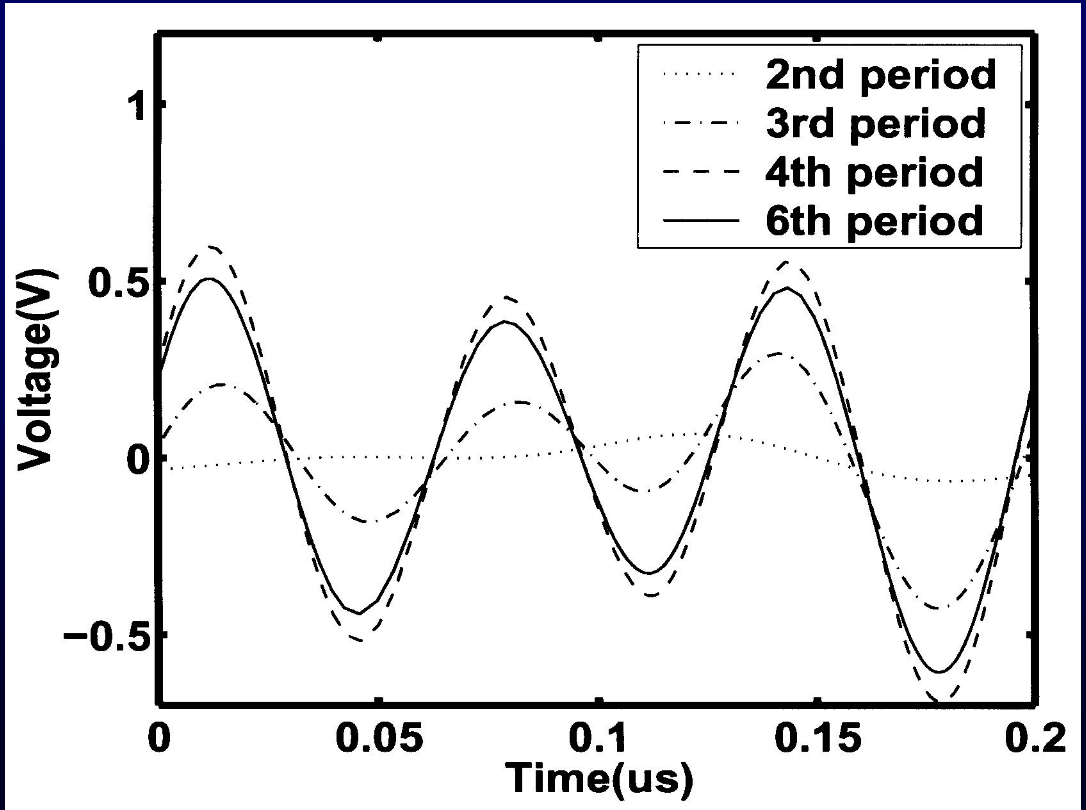
- Two-point boundary value problem

$$X(0) - X(T, X(0)) = 0$$



Frequency Multiplier Example

- Shooting method: 6 periods
- Conventional transient: 1500 periods



Harmonic Balance Method

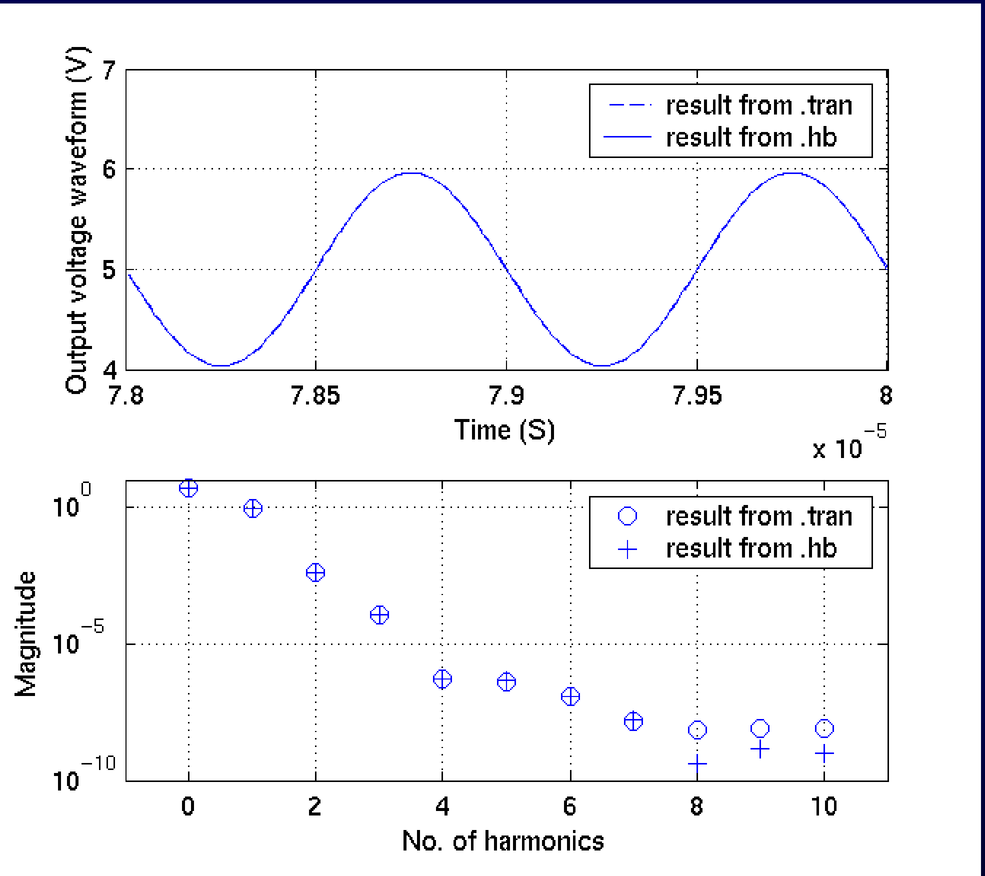
- Truncated Fourier series approximation of $x(t)$

$$x(t) \approx a_0 + \sum_{i=1}^{s} (a_i \cos(\omega_i t) + b_i \sin(\omega_i t))$$

- For 2s+1 time samples $x_0 \ldots x_{2s}$

$$\mathbf{x} = \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{2s} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & \cos(\omega_1 t_0) & \cdots & \sin(\omega_s t_0) \\ 1 & \cos(\omega_1 t_1) & \cdots & \sin(\omega_s t_1) \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \cos(\omega_1 t_{2s}) & \cdots & \sin(\omega_s t_{2s}) \end{bmatrix}}_{\Gamma^{-1}} \underbrace{\begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ b_s \end{bmatrix}}_{\mathbf{X}} = \Gamma^{-1} \mathbf{X}$$

MOSFET Tuned Amplifier



- 2D numerical MOSFET with 31x19 mesh points
- 10 harmonics
- # iterations = 6
- Result verified by transient simulation

Periodic Steady-State Analysis: Performance Results

Circuit	Shooting Method		Harmonic balance	
	# Iter	Time (sec)	# Iter	Time (sec)
Simple rectifier	2	28	16	37
DC power supply	6	81	39	45
CB amplifier	4	254	53	385
X3 freq. multiplier	6	10	8	32
MOS CS amplifier	3	554	6	36

Simulation of Microsystems

- **Microdevice simulation**
  - Finite-element methods (FEM)
  - Fast integral methods
- **Simulation of complete systems**
  - Lumped equivalent circuit representations
  - Macromodels derived from FEM analysis
  - Analog hardware description language (AHDL) descriptions

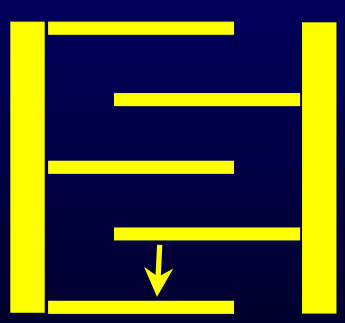
Limitations of High-Level Models

- Typically derived for small-signal conditions
- Not suitable for systems with feedback
- Cannot predict behavior outside range

Beam bending

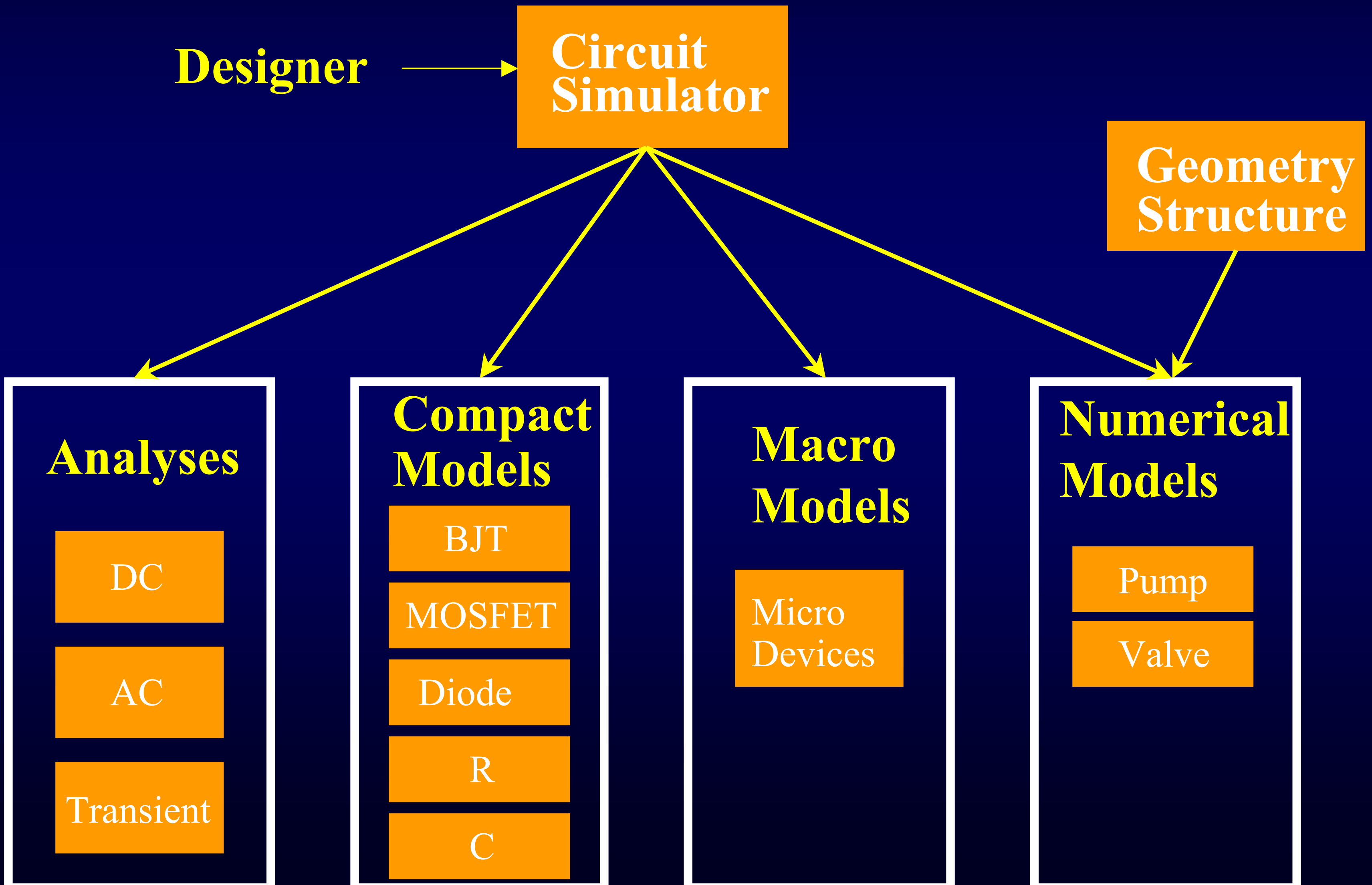
reach substrate

Comb structure



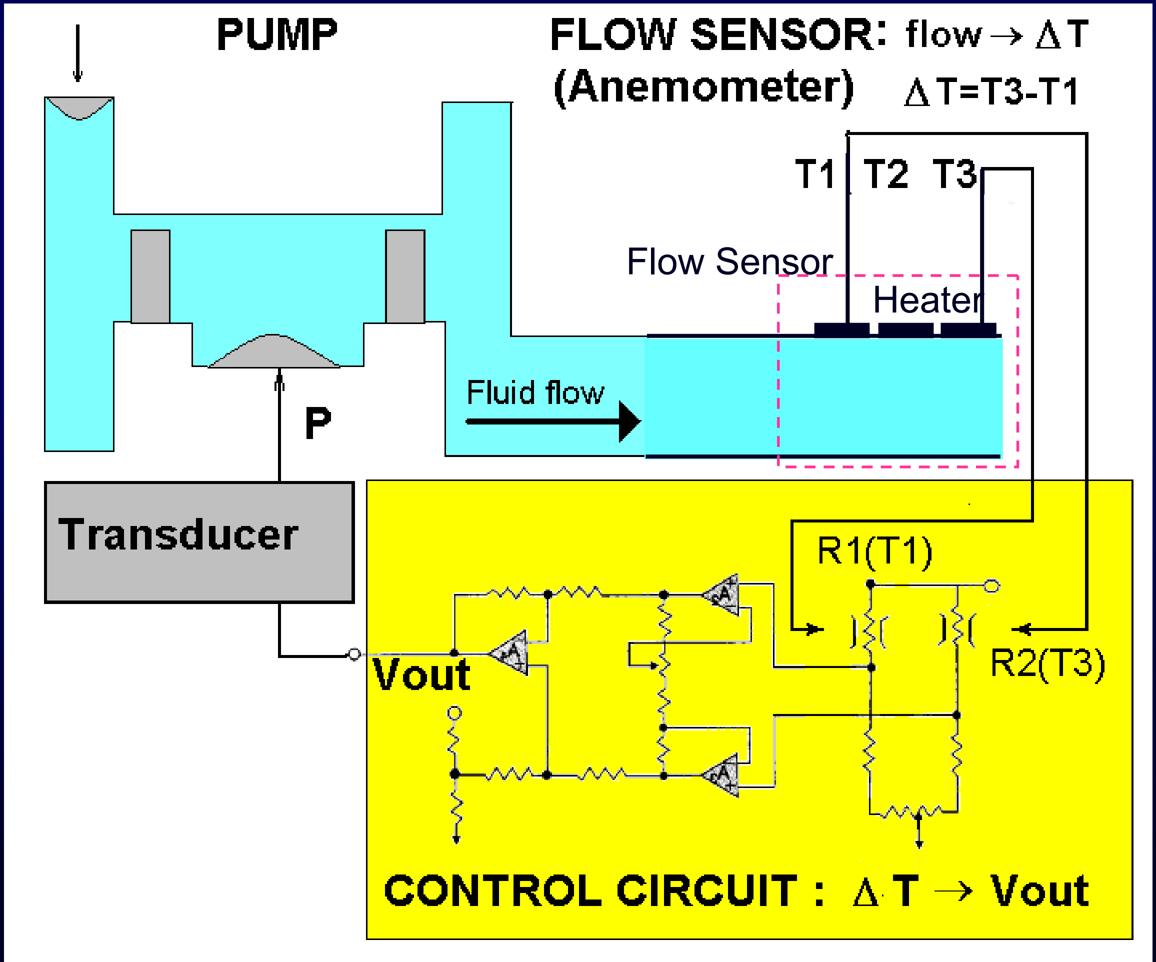
reach limit stops

Coupled Circuit/Microdevice Simulator

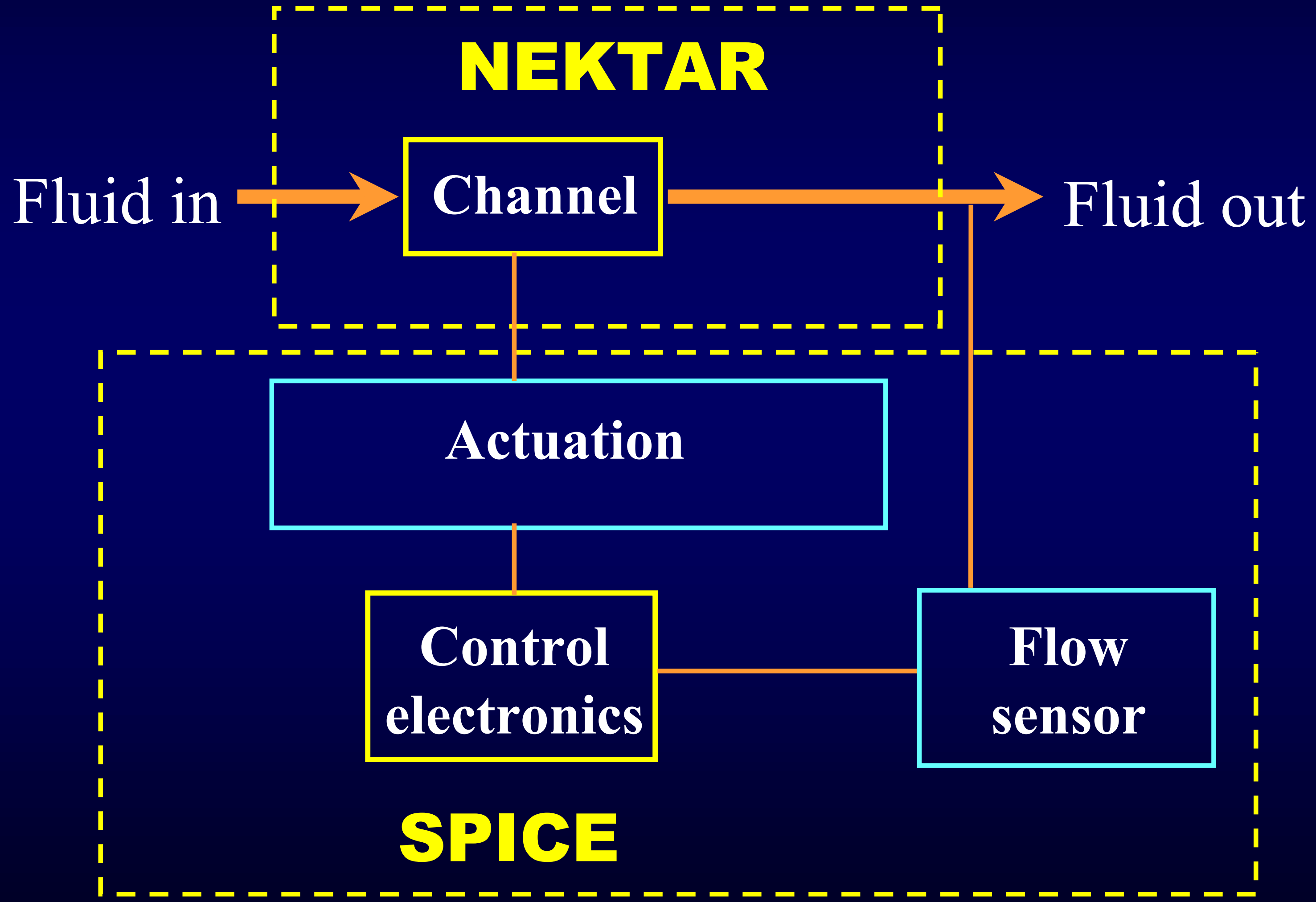


Micro Fluidic Simulation Example

- Constant flow system

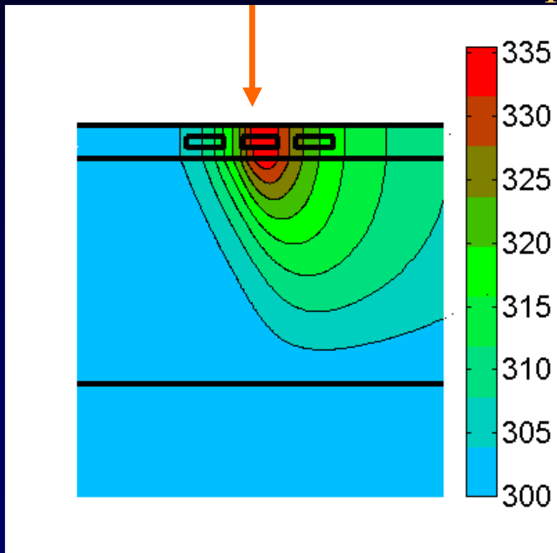


Simulator Interaction

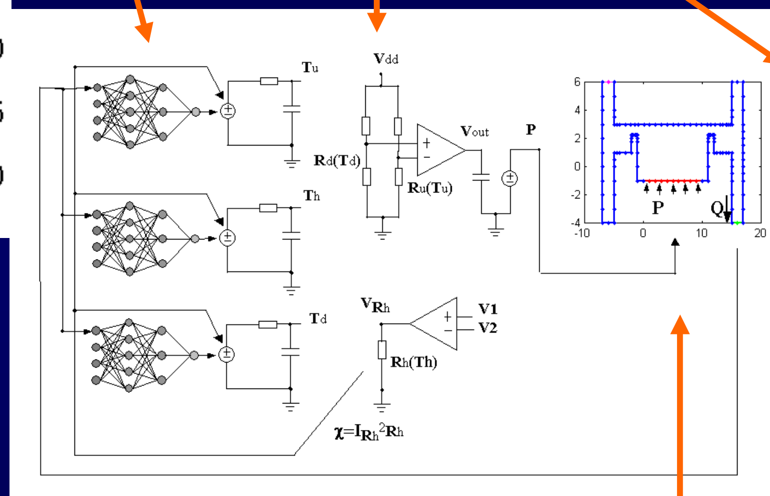


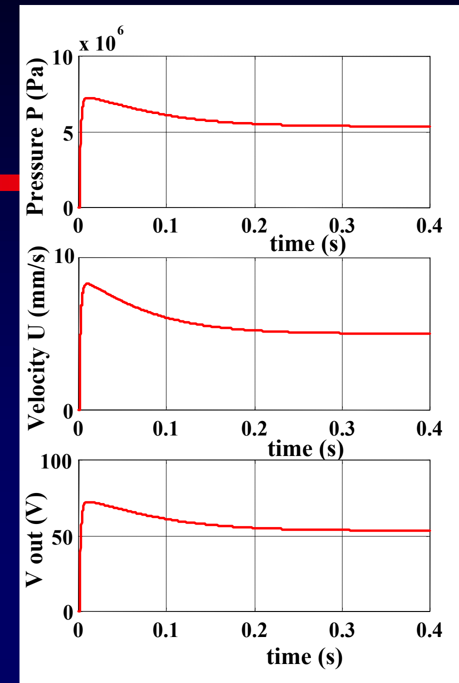
Coupled System Simulation: 4 Physical Domains

Flow sensor: Flow to Temperature (thermal domain)

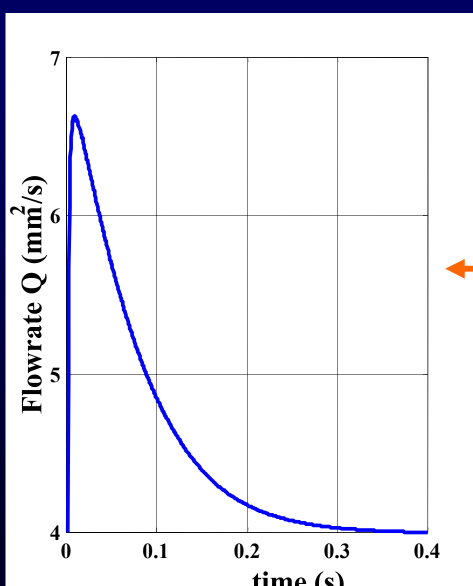


Circuit: Temperature to Voltage (electrical domain)

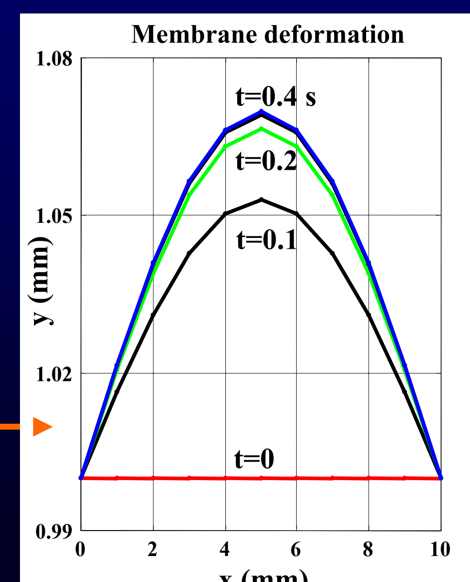




Micropump: Displacement to Flow (fluid domain)



Piezo-actuator: Voltage to Displacement (structure domain)



Conclusions

- Coupled circuit/device simulations required for accurate simulation of circuits/systems
- Provides a direct link between technology changes and circuit performance
- Also useful for developing accurate compact models
- Need faster solution methods for PDEs
- Different coupling algorithms need to be developed for various problem domains