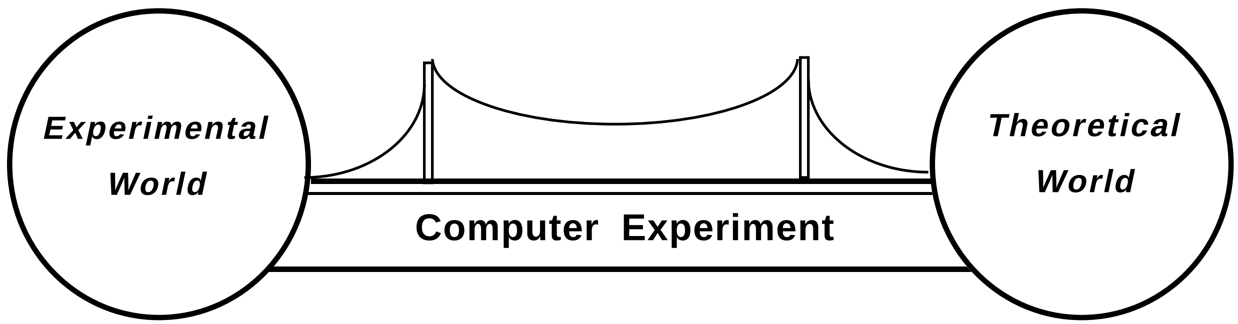
Role of Computer Experiment



Accumulation of factual information

→ ***Checks and stimuli*** ←

Ordering of factual information into logically coherent patterns to provide predictive laws

Physical experiment ↔ **Computer experiment** ↔ **Theory**

Apparatus
+
data analysis

- Devices are expensive
- Data is inaccessible
- Phenomena are very complex

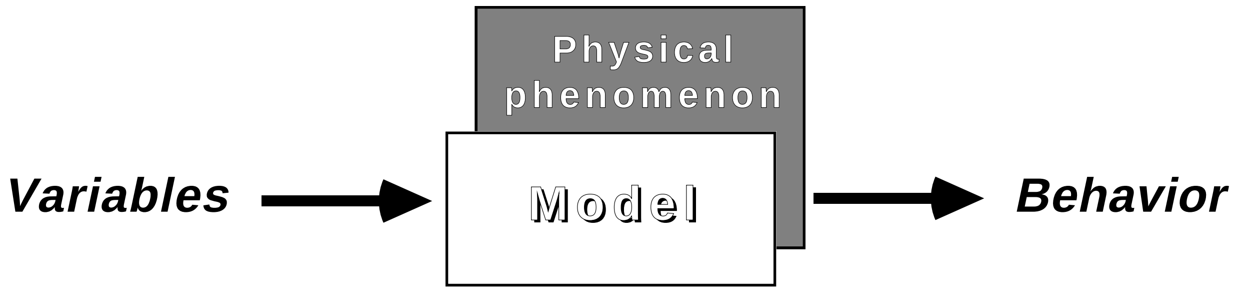
Computer
+
simulation program

{ *Complementing experiments/theory when* }

Mathematicl analysis
+
numerical evaluation

- Nonlinearity
- Many degree of freedom
- Lack of symmetry

A Word About Modeling



- ❑ **Modeling — *Approximation*** (different levels)
- ❑ **Simulation — *Trade-off*** (different considerations)

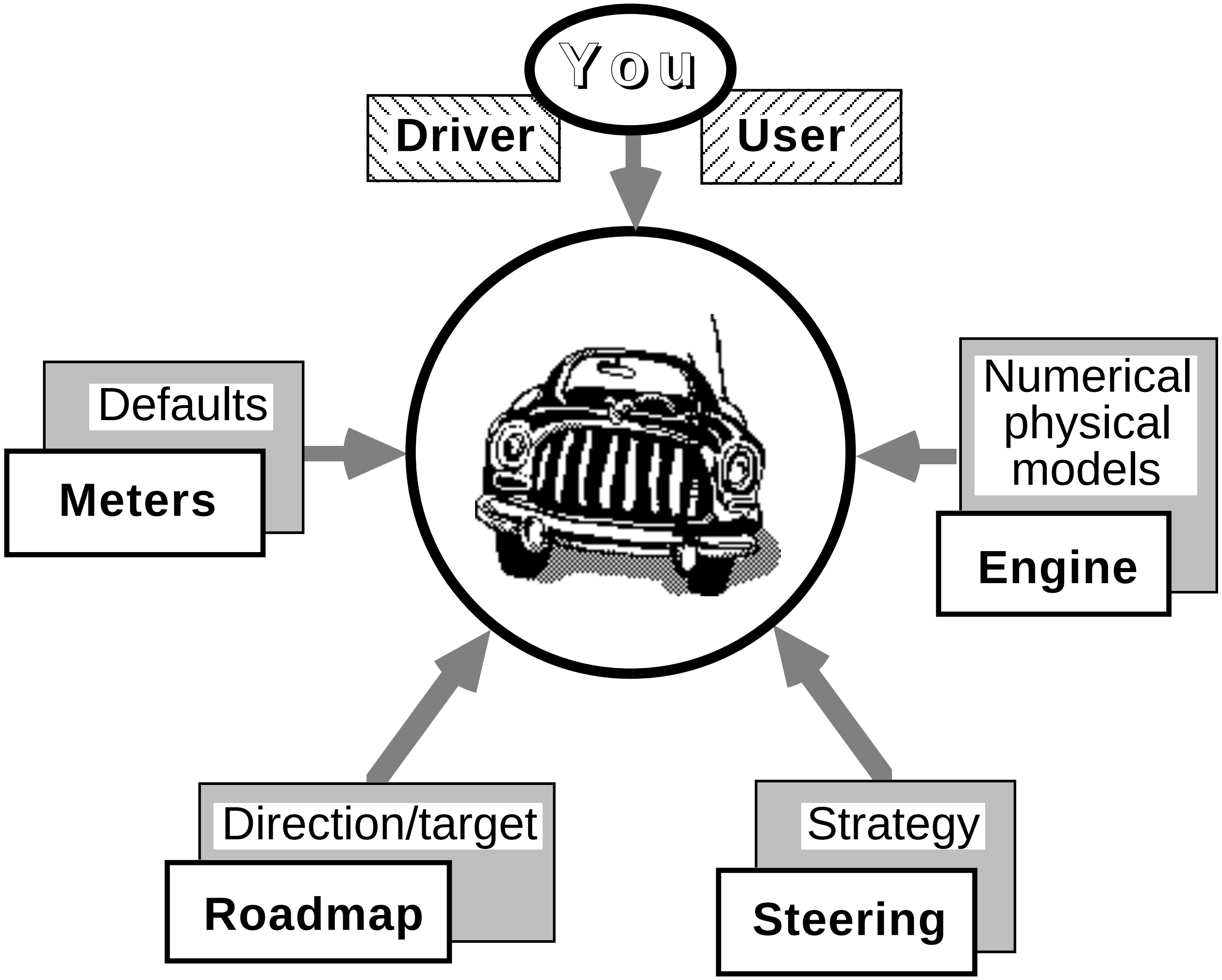
"A model of a physical device is a mathematical entity with precise laws relating its variables. The model is always distinct from the physical device, though its behavior ordinarily approximates that of the physical device represented. Thus a model is never strictly equivalent to the device it represents."

— John Linvill

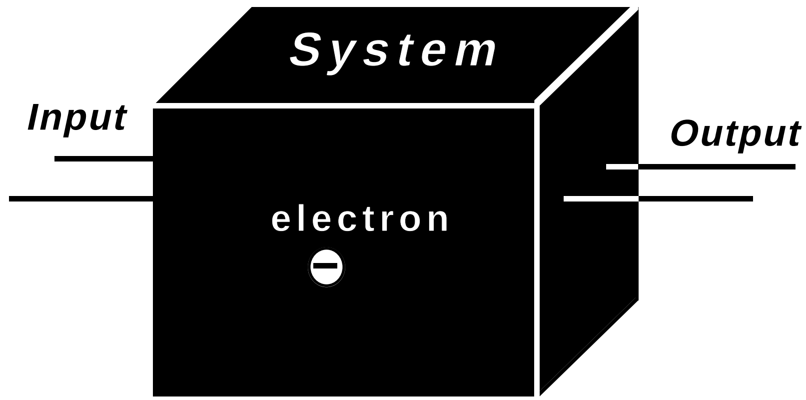
"Everything should be made as simple as possible, but not any simpler."

— Albert Einstein

Driving the Simulation Vehicle



Electronic Systems

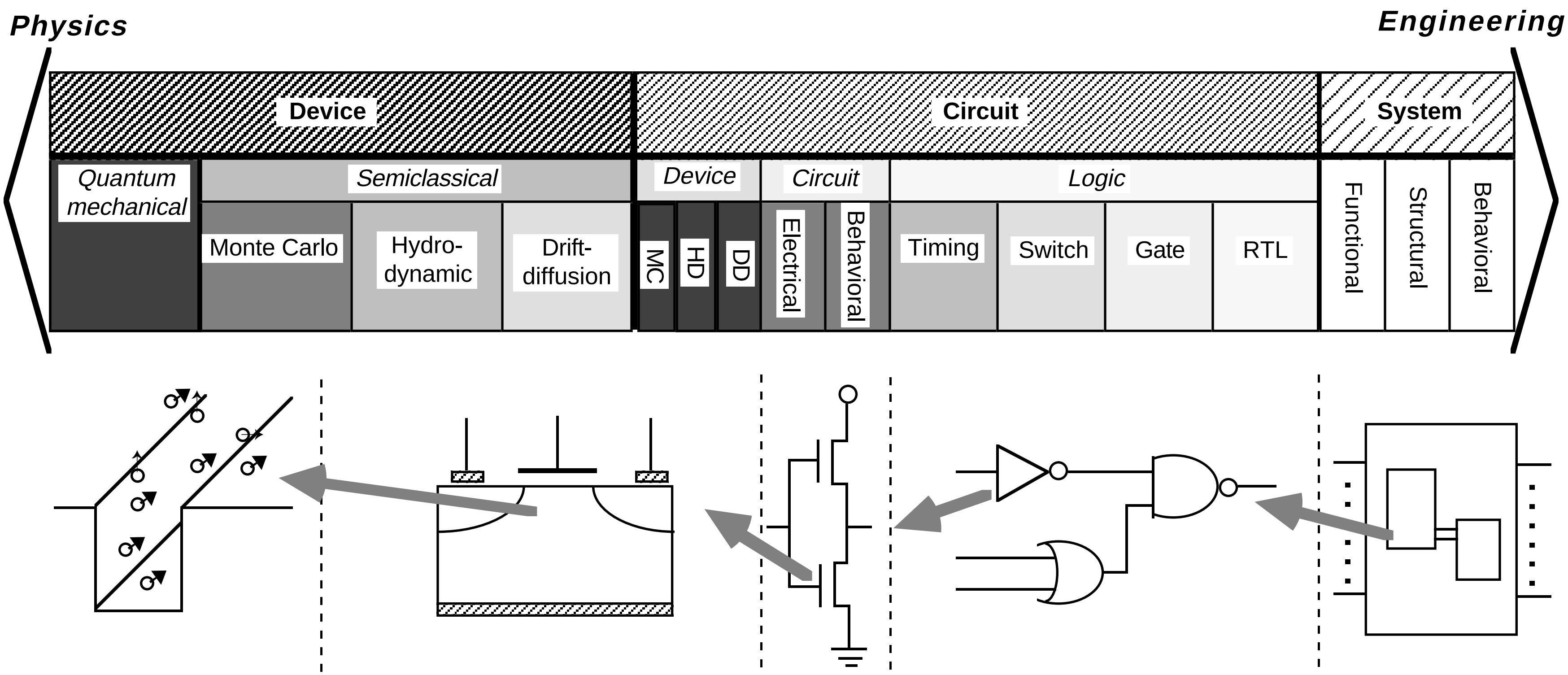


Electronic System* — A *black box* which performs a certain function based on the laws of physics of the *electrons

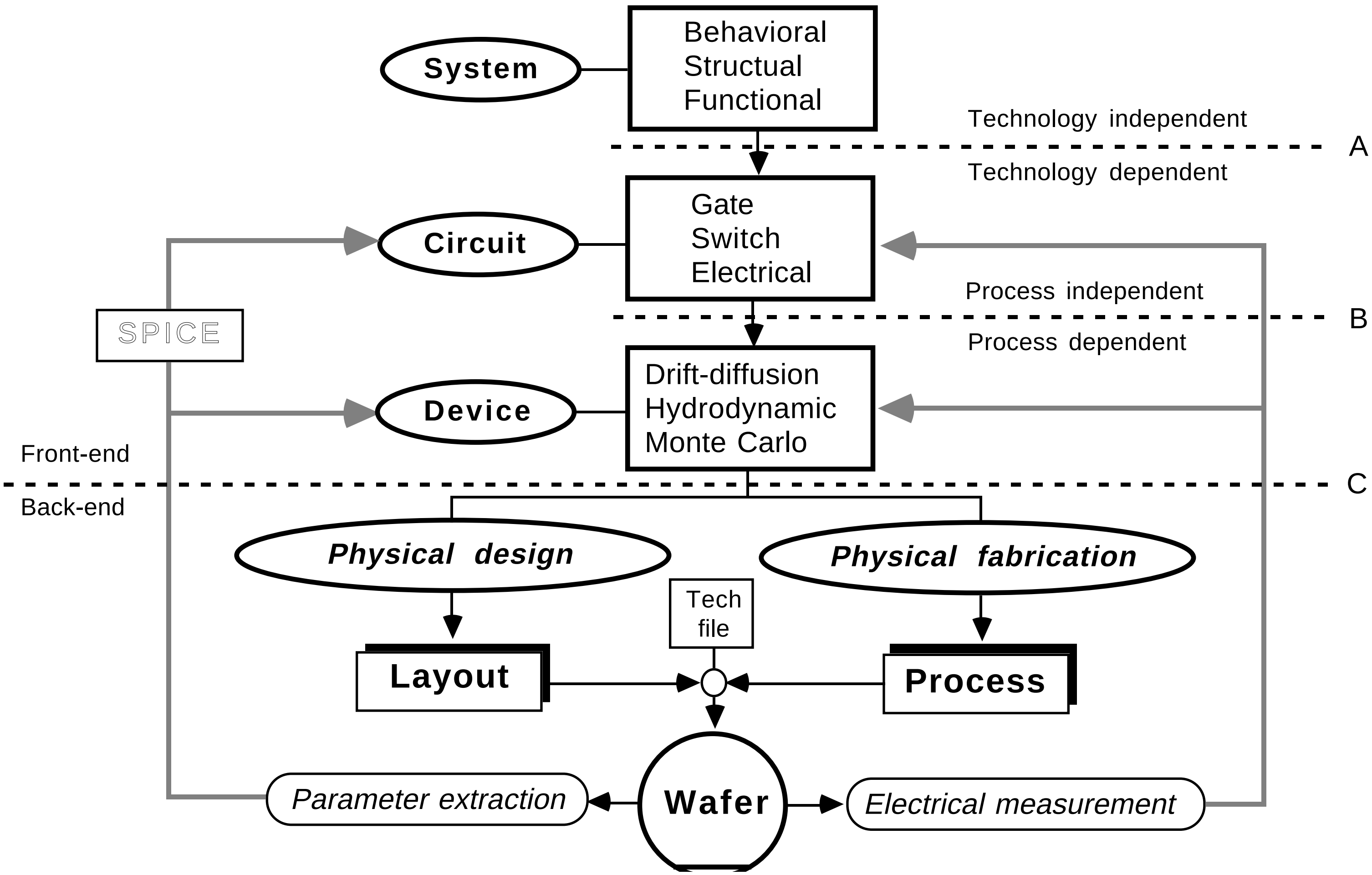
Whenever you press the button of an electronic system, you are actually manipulating the motion of individual electrons.

Spectrum of Approaches to Analyzing Electronic System

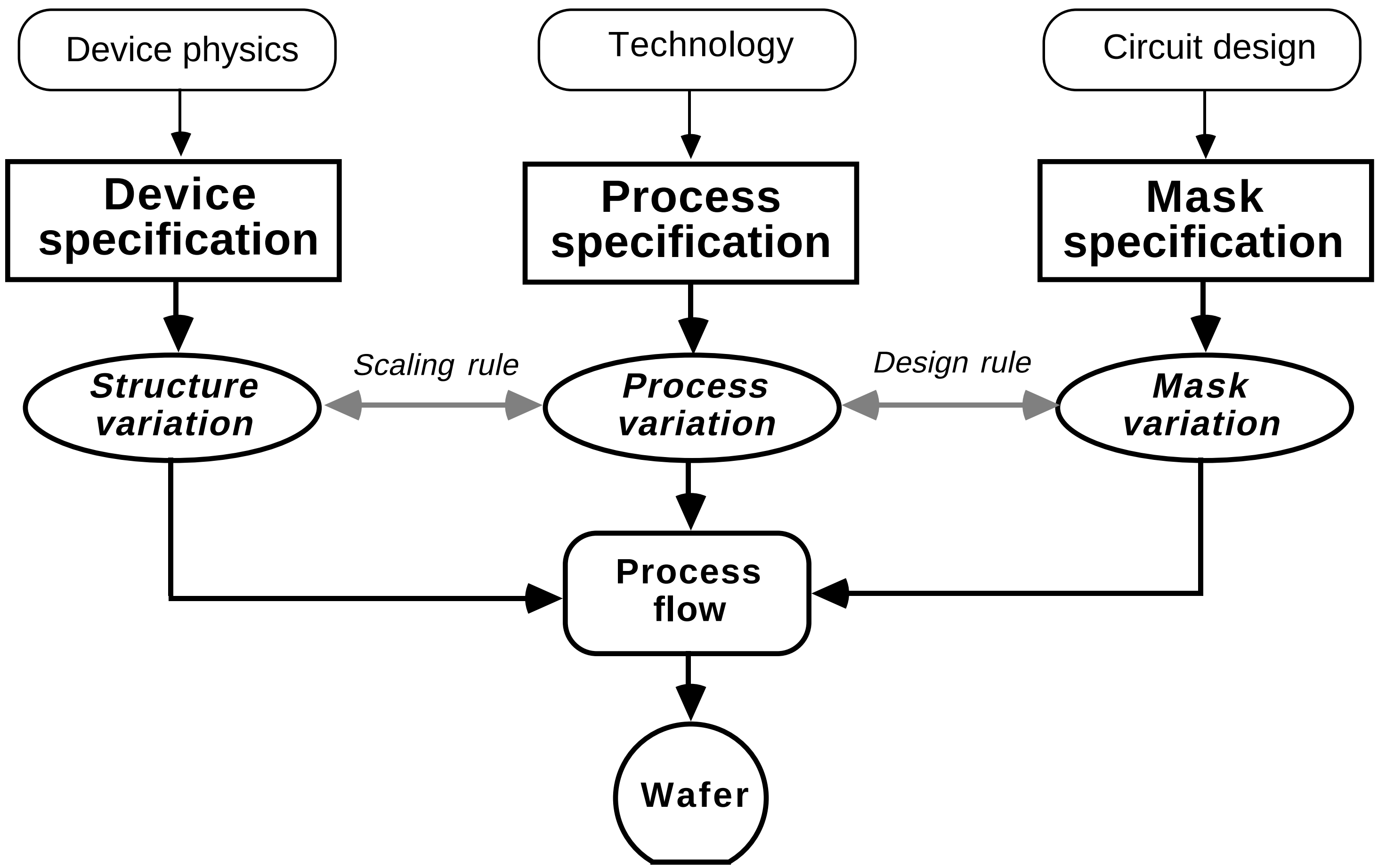
The "Big Picture"



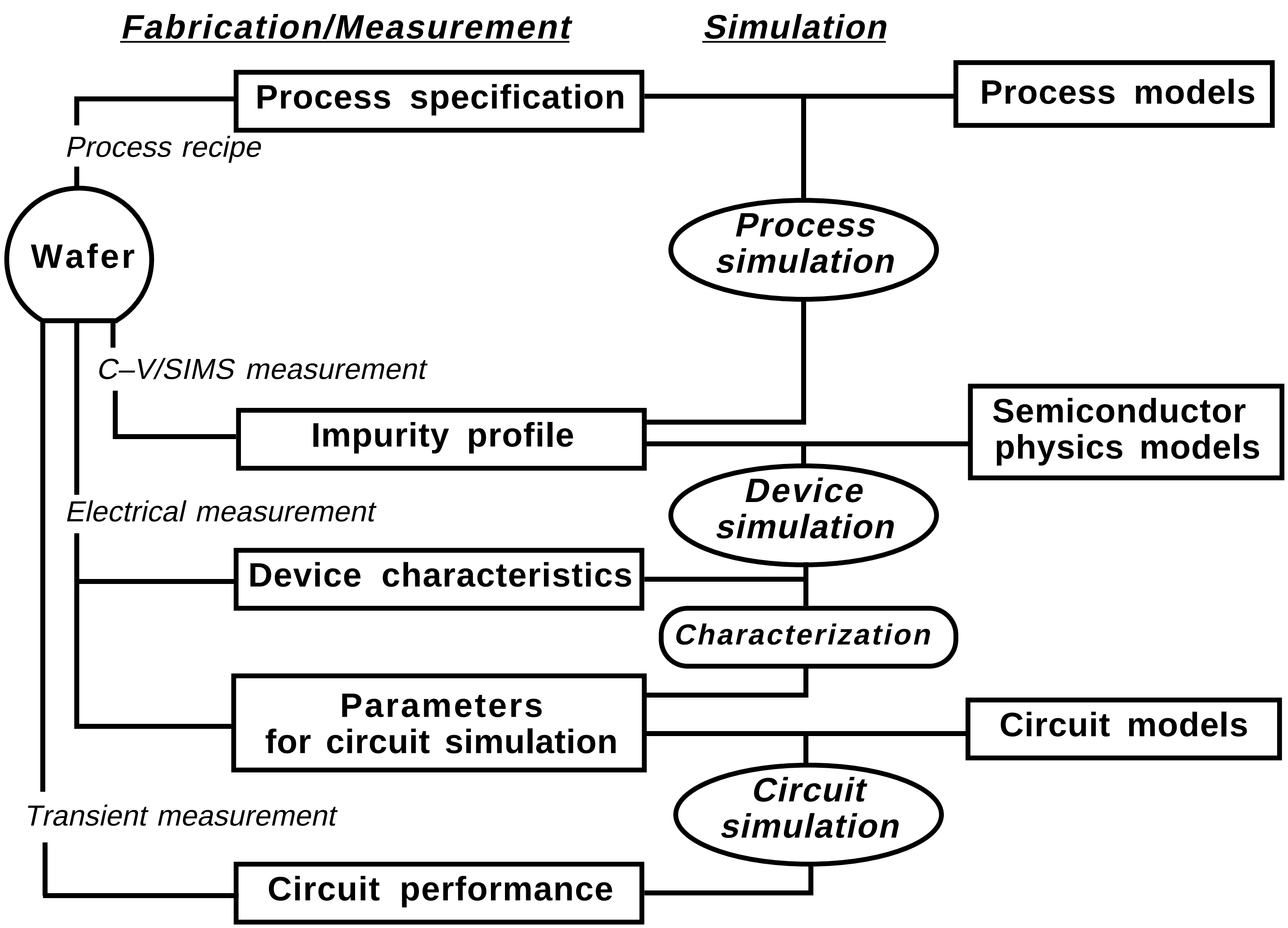
VLSI Design and Manufacturing Hierarachy



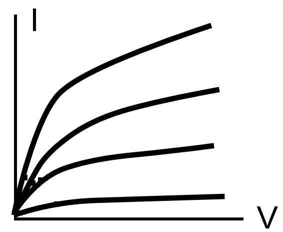
VLSI Technology Development



VLSI Process Development



Three Ways of Obtaining Device Characteristics



Experimental

- Wafer
- SMU, oscilloscope

Numerical

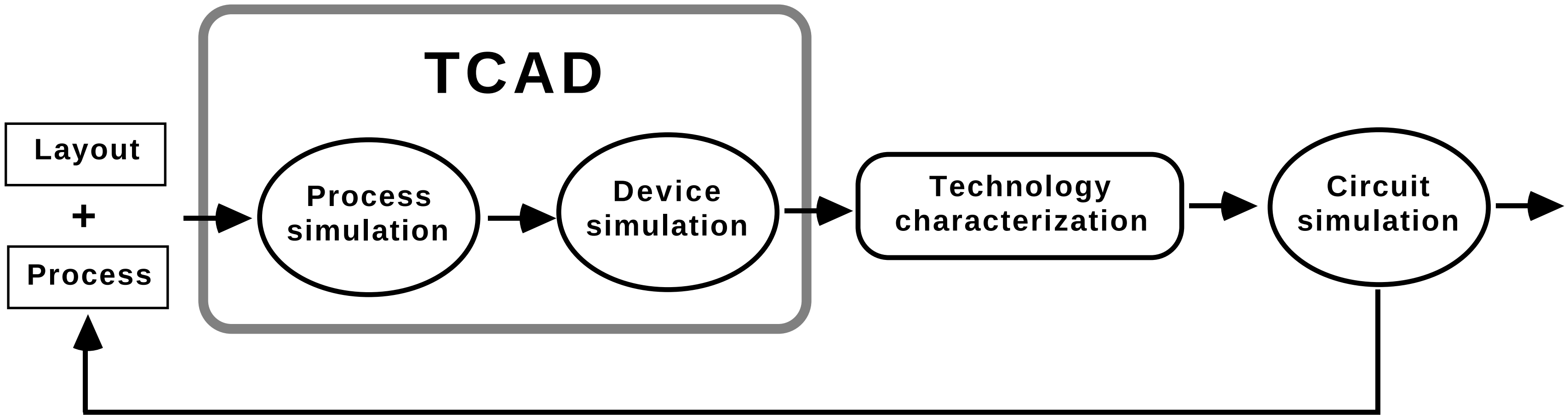
- Partial differential equations + B.C.'s
- 2D/3D grid, finite-element
- MEDICI

Analytical

- Closed-form equations
- Matrix, iteration
- SPICE

- ***What are the advantages of the numerical approach to device characterization?***

TCAD — Physical Simulation



- Goal: Emulate physical phenomena — *"virtual" wafer fabrication*
  - ❏ Semiconductor processing
  - ❏ Device operation and electrical characterization
  - ❏ Parasitic electrical effects
  - ❏ Circuit performance

The Driving Force — Deep Submicron Technology

❏ **New device physics**

- Pushing to the limit of conventional device modeling (“drift-diffusion”)
- Requiring advanced physical models and quantitative accuracy (3D)

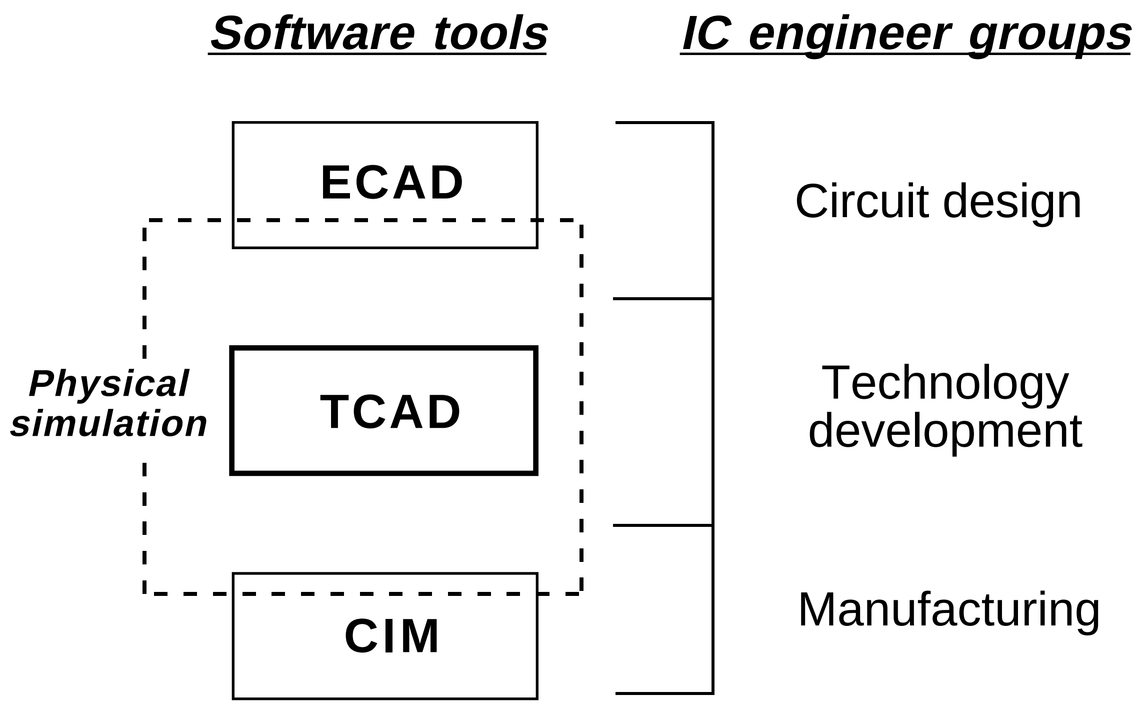
❏ **New technologies**

- Pushing to the optical limit of conventional masking
- Requiring advanced processing technologies (E-beam, …)

❏ **New design methodologies**

- Interconnect parasitic plays a more critical role
- Multilayer technology complicates topography
- Maximum IC performance requires full-cell characterization

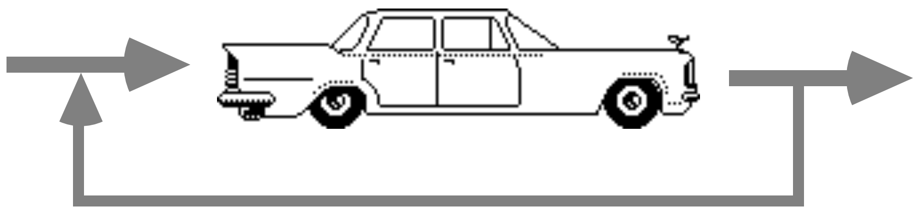
Role of TCAD in IC Engineering



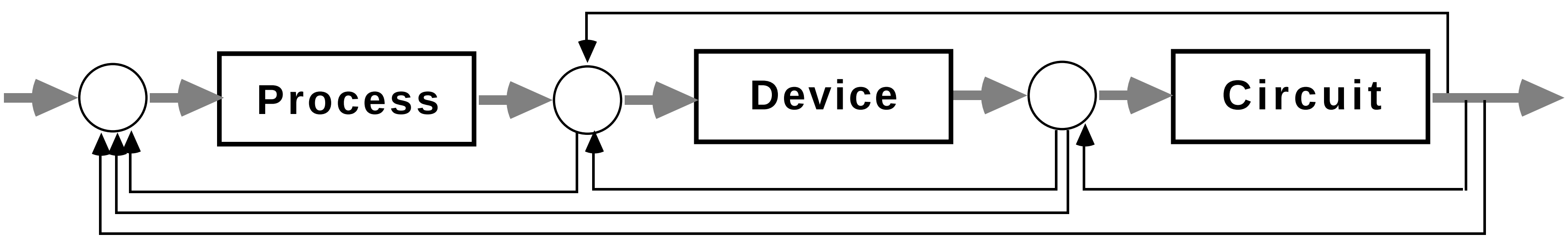
Three Major Stages of Physical Simulation

Stage	***Motivation/Goal***
Process Simulation	• Process alternative evaluation • Process sensitivity investigation • Process centering and yield improvement
Device Simulation	• Understanding physical effects • Electrical characteristics prediction • Device reliability study
Technology Characterization	• Device parameter extraction and optimization for circuit design • Interconnect parasitic extraction for signal integrity analysis • Full-cell extraction for technology development and library characterization

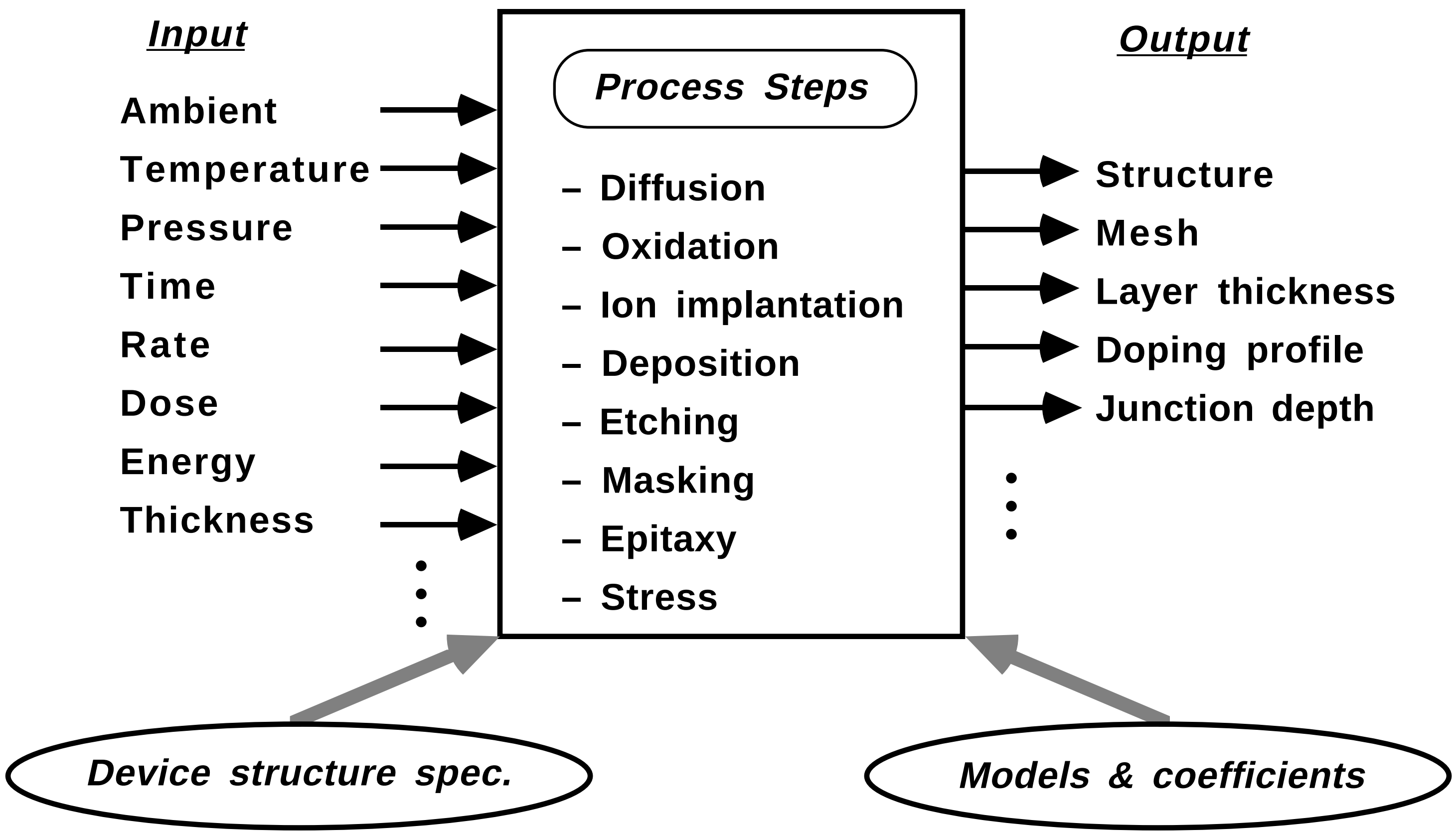
The Simulation Vehicle



- **The simulator:** The “numerical engine” of the “simulation vehicle.”
- **Back and front:** What are the input and output parameters?
- **Under the hood:** What are the physical models?
- ***The key to effective use of a simulation tool is to know what it is capable, and to use it as your <u>tool</u>, not your <u>goal</u>.***



Process Simulation



Device Simulation

Input

Process
- Structure
- Mesh
- Doping

User
- Grid
- Mesh
- Analytic profile

Physical Models
- Recombination
- Bandgap/DOS
- Mobility
- Statistics

Boundary Conditions
- Ohmic/Schottky
- Insulator/Neumann
- Interface charge/traps
- Lumped/distributed RC

Numerical Methods
- Decoupled (Gummel)
- Coupled (Newton)
- Linear matrix
- Jacobian matrix

Analyses
- Transient
- Small-signal AC
- Impact ionization
- Gate current

Output

Terminal characteristics
I–V, G–V, C–V

1D plots (along a line segment)
Potential, field, band-edge, Fermi-level, doping, carrier temperture, carrier concentration, generation/recombination rate, current density

2D plots
Region boundaries, junctions, depletion regions, ...

3D plots (same quantities as 1D)

Surface (projection of a 3D view)

Vector (field, current density)

Contour (same quantities as 1D)

Technology Characterization

Input

Measured or simulated electrical characteristics →

Device Parameter

Models

– Built-in: MOS/BSIM, BJT, JFET, ...

Variables

– Voltage, geometry, temperature

Targets

– Currents

Optimization

– Data selection/weighting

→ **Output**

SPICE model parameters

Input

- Lithography →
- Topography →
- GDS II →

Interconnect Parasitic

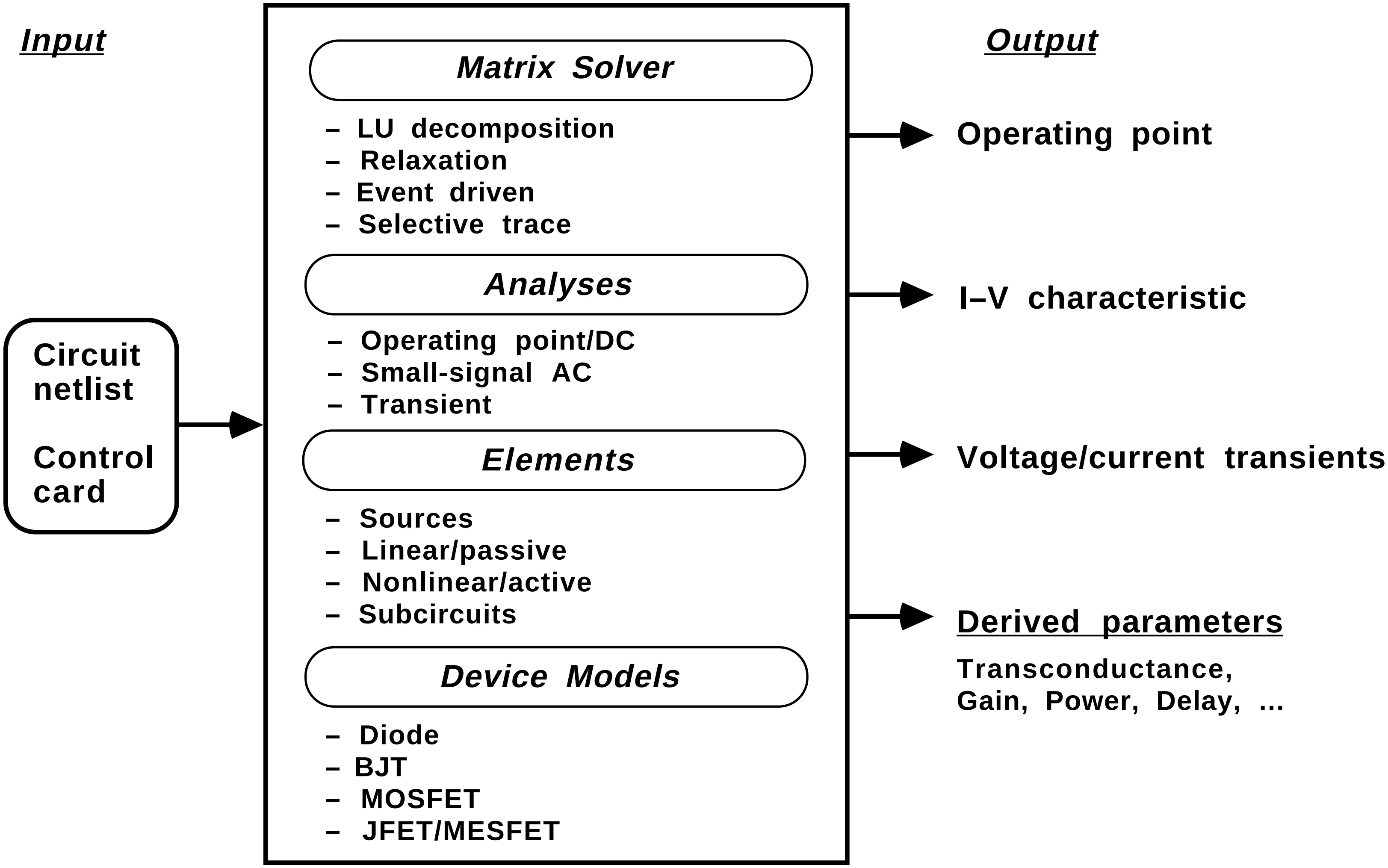
2D/3D solver engine

High-frequency analysis (including skin effect)

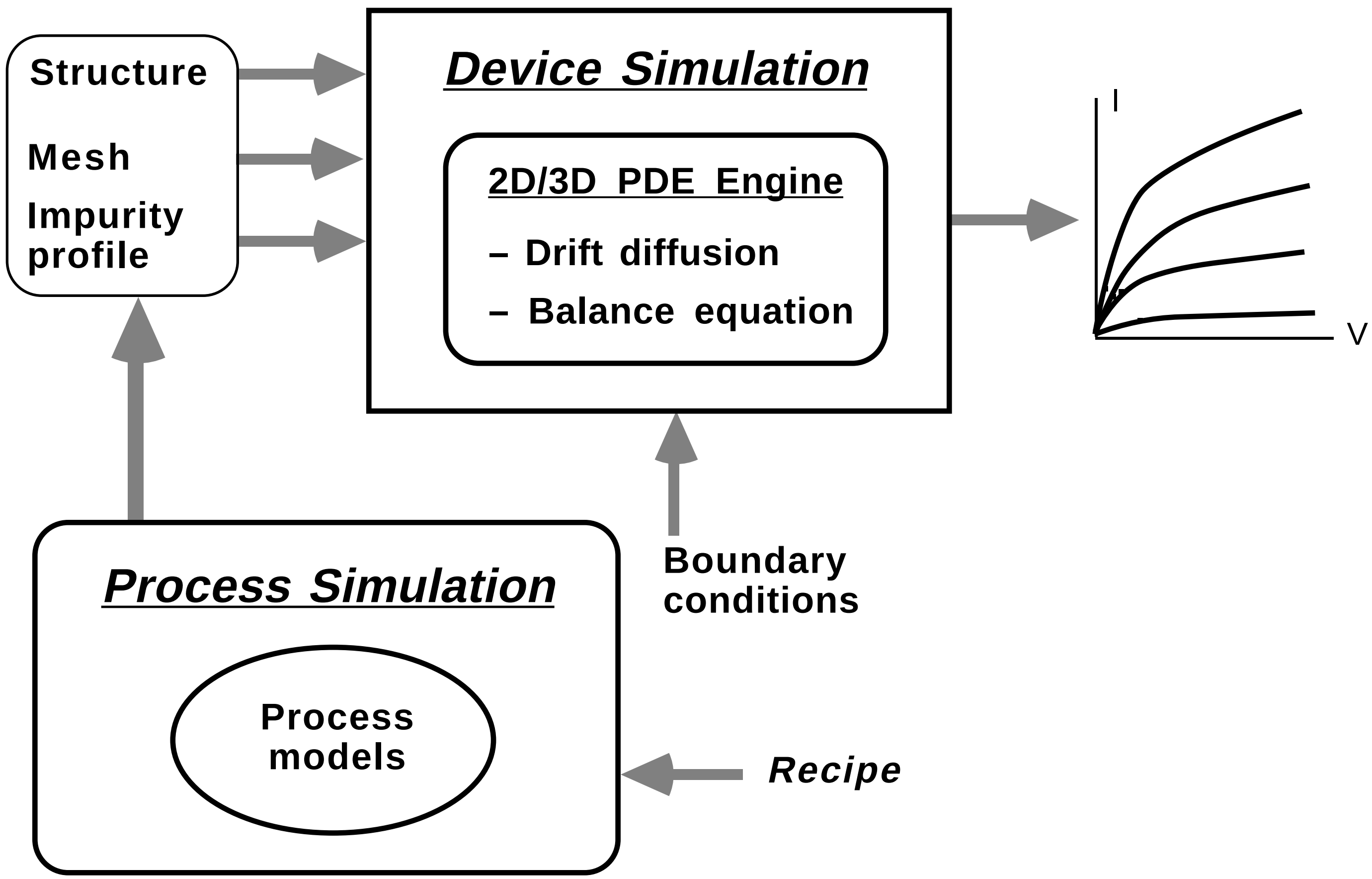
Output

- → SPICE equivalent RLC netlist
- → Distributions: potential, current density, temperature
- → RSM model from regression analysis: analytic models, rules for LPE
- → 3D cell-level interconnect extraction

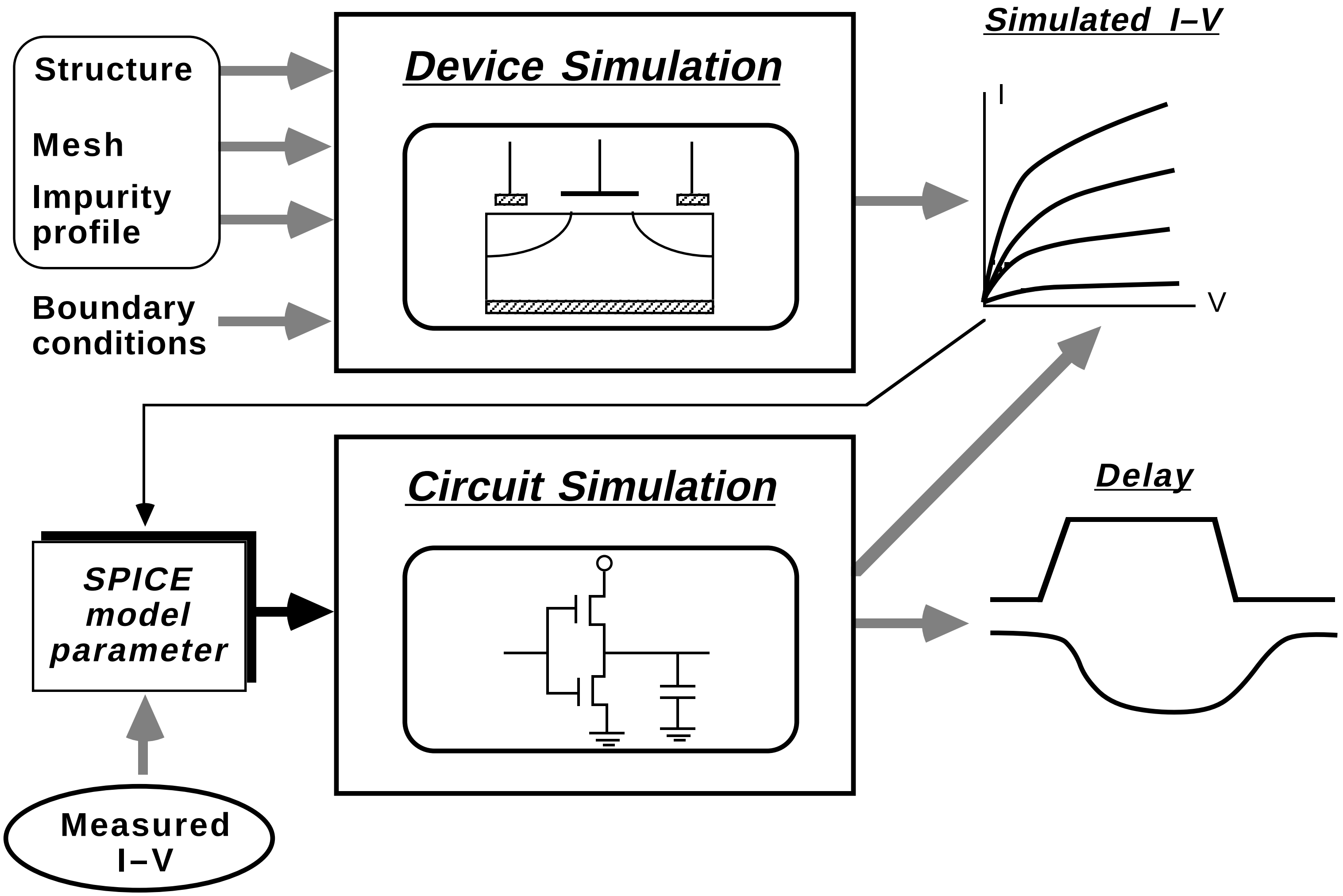
Circuit Simulation



Device vs Process Simulation



Device vs Circuit Simulation



Role of Process and Device Simulation

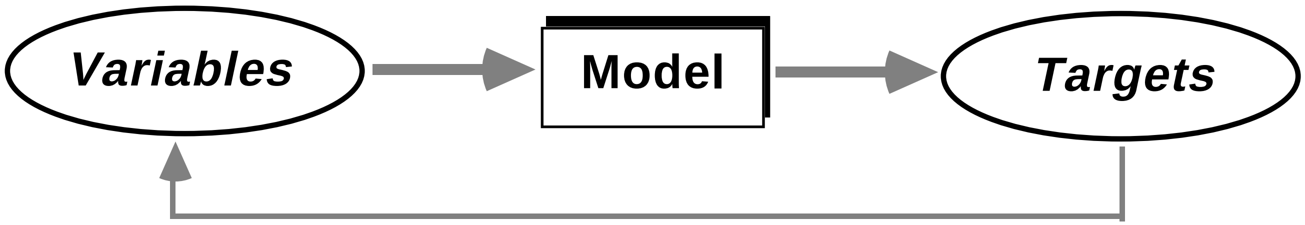
❏ Process simulation

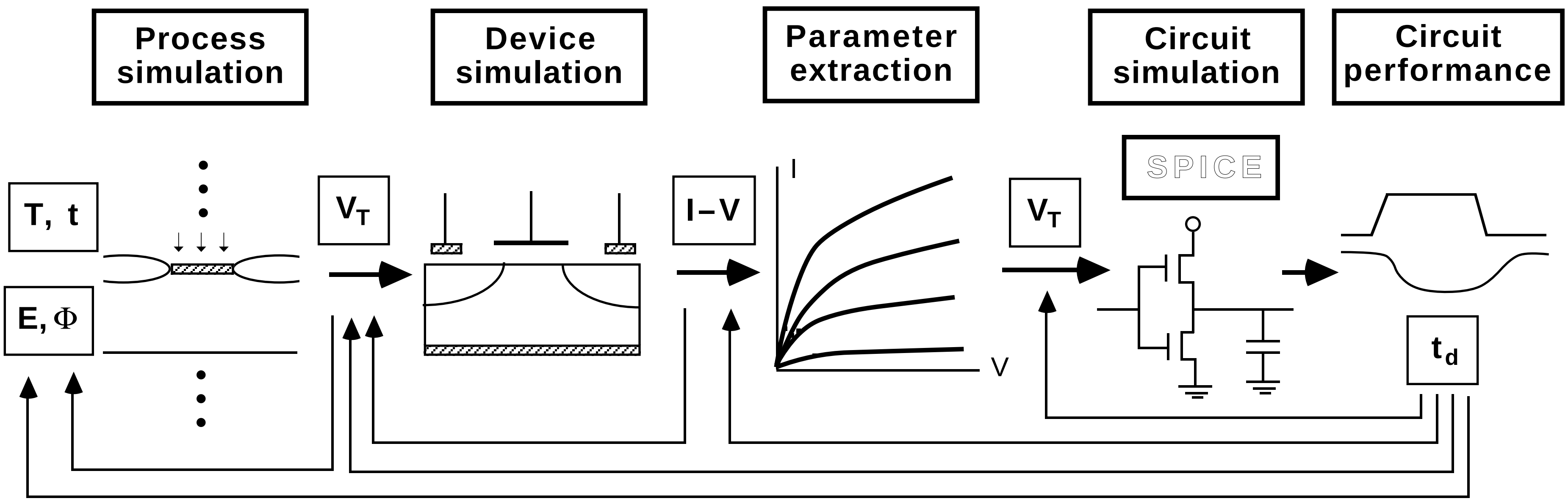
- ***Stand-alone***: simulate processing steps for evaluating process alternatives, sensitivity, and yield improvement
- ***Front-end to device simulator***: provide realistic structure and impurity profile for meaningful device simulation

❏ Device simulation

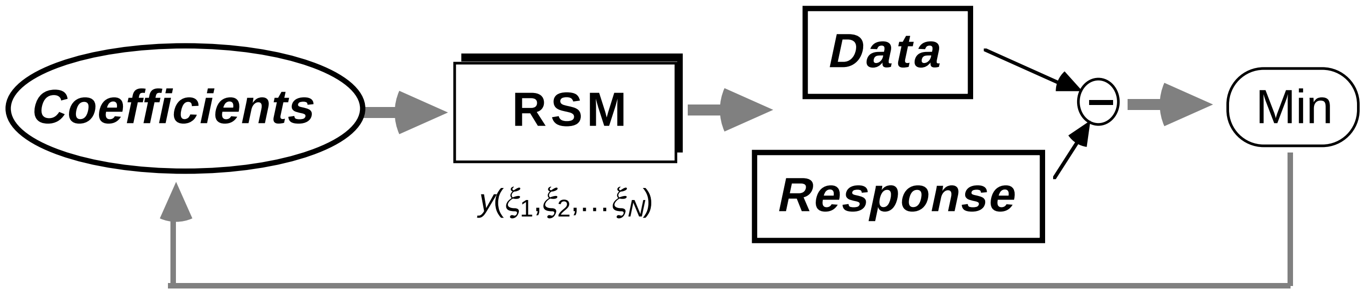
- ***Stand-alone***: simulate single-device electrical characteristics for understanding physical effects, advanced device design, and reliability study
- ***Front-end to circuit simulator***: provide accurate parameters for transistor-level models to predict circuit performance

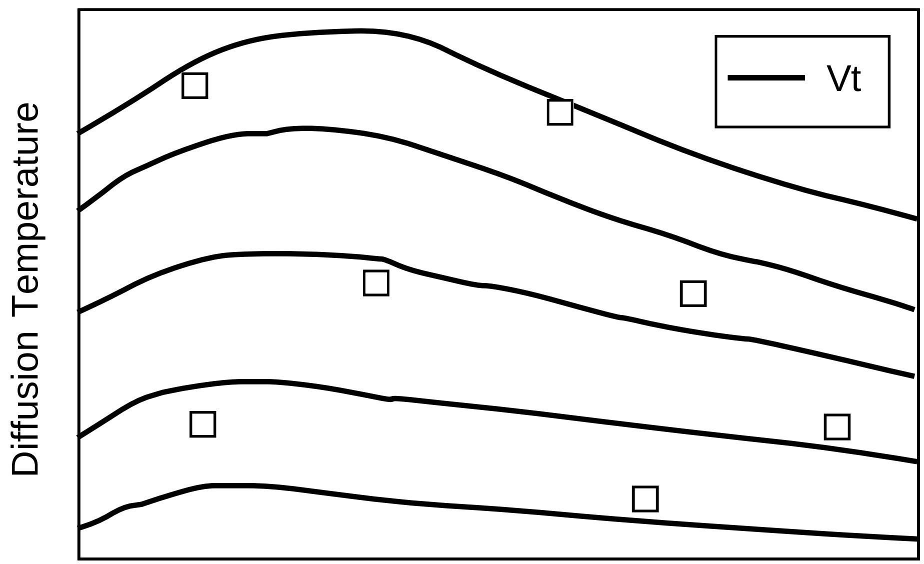
Design of Experiment (DOE)



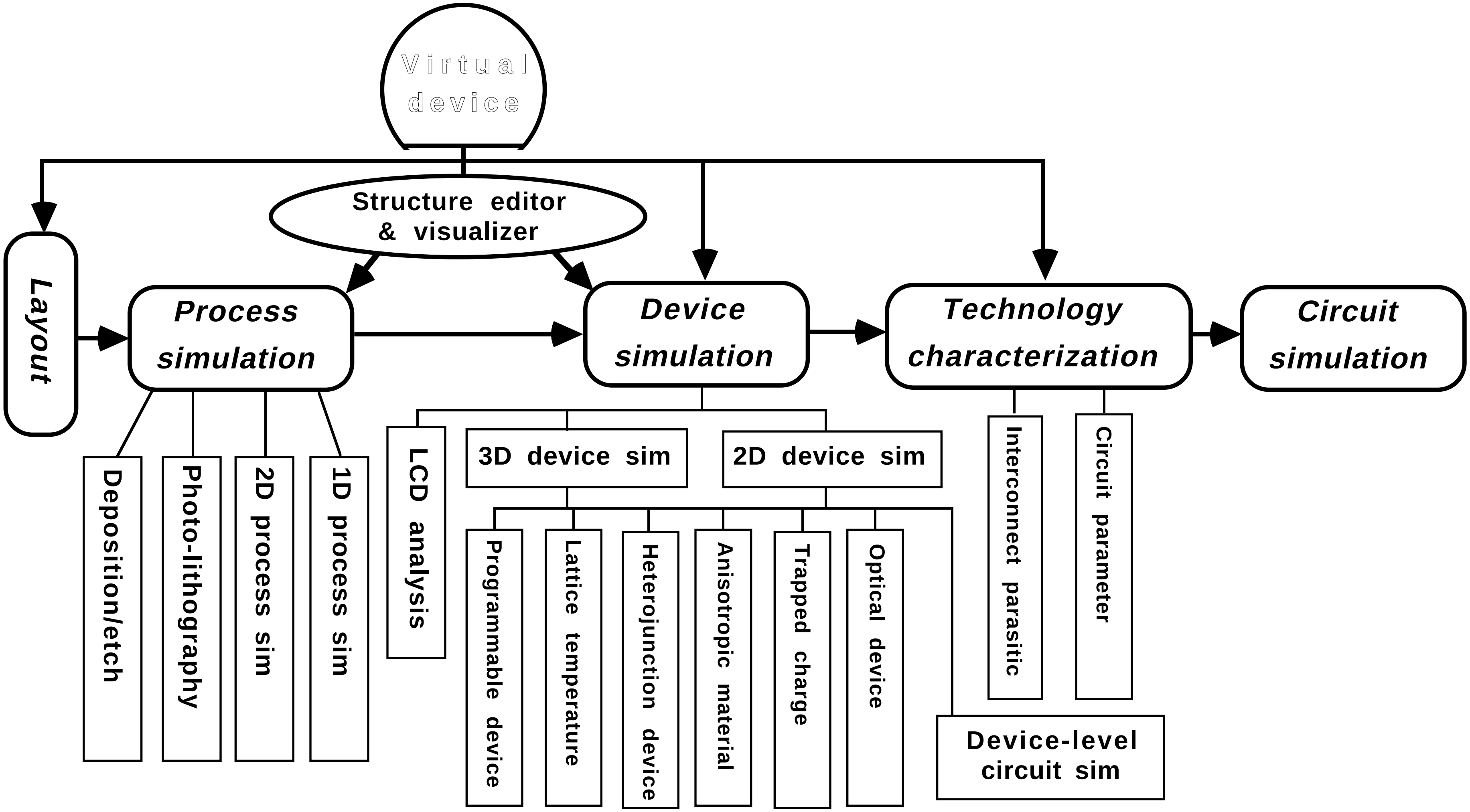


Response Surface Modeling (RSM)

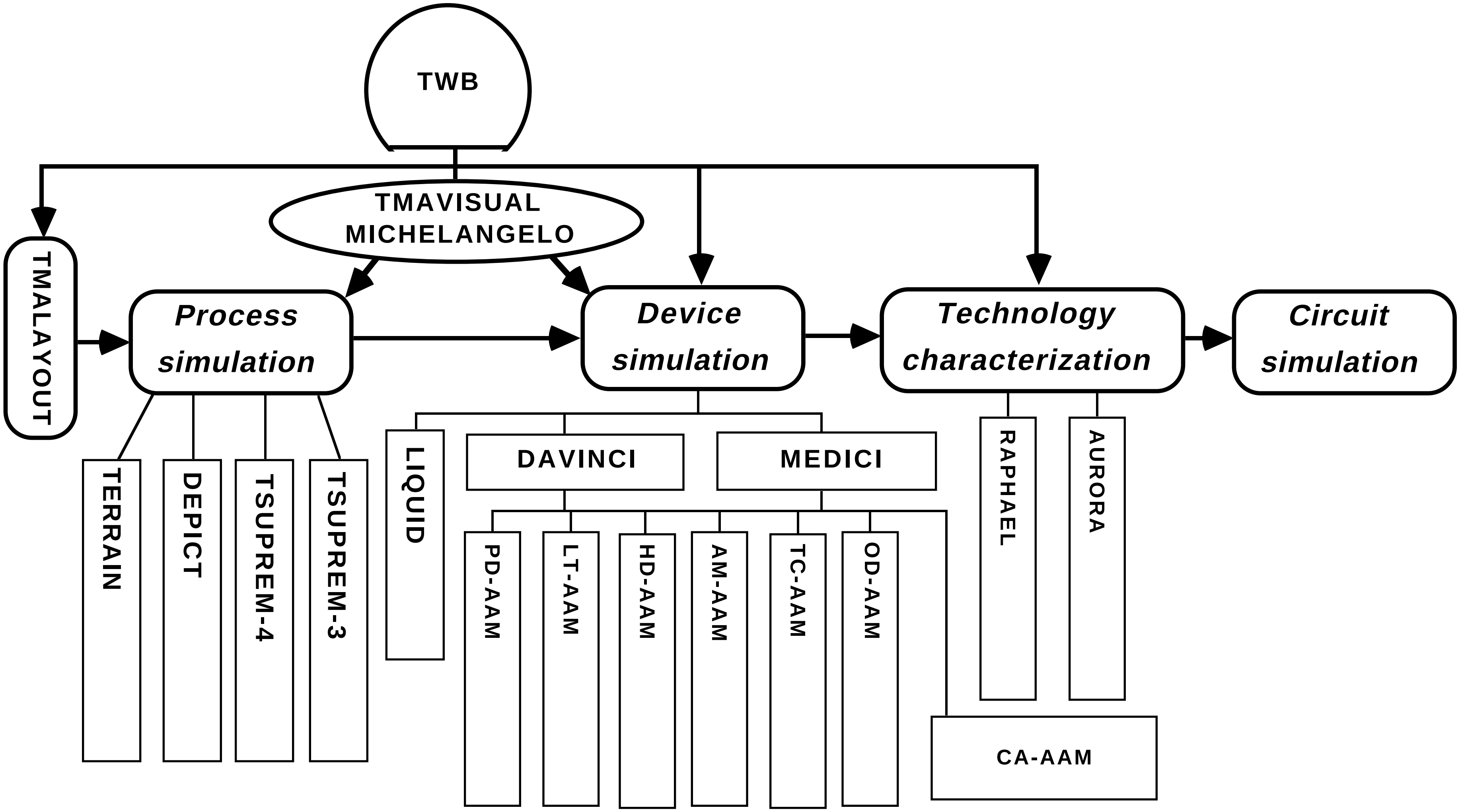




Virtual Device Fabrication



TCAD Tools from Technology Modeling Associates



Simulator Accuracy

❑ **Relative accuracy of a simulator** — basic usage

- An "inaccurate" simulator can provide *relatively* "accurate" results in terms of the valuable insight into the different variable–target dependencies

❑ **Absolute accuracy of a simulator** — ultimate goal

- Accuracy of models (→ ***physics***)
- Accuracy of model coefficients (→ ***calibration***)

❑ **Accuracy of simulations**

Accuracy of simulator + *Proper* use of simulator

● **Essence of simulation** — trade-off between accuracy and speed

General Tips on Using CAD Tools

- **A simulator is only as good as the physics put into it**
    - Only what is well understood can be modeled
    - Always with clear objectives for a simulation
    - Rely on your own judgement, not simulation nor experimental results
- **Be fully aware of the model *assumptions* and the *default* parameters**
    - Make sure the model is used in its region of validity
    - Justify if defaults are to be used
- **The result of a simulation is *grid dependent***
    - Trade-off between accuracy and speed
    - Use coarse grids initially, refine the grids as you proceed
- **Look for *trends*, not for "accurate" values**
    - Never try to "perfectly fit" a single set of parameters to an experimental curve
    - Overall 10–20% accuracy would be a reasonably good fit