PACT: A SPICE-Based Parallel Compact Thermal Simulator for Fast Analysis

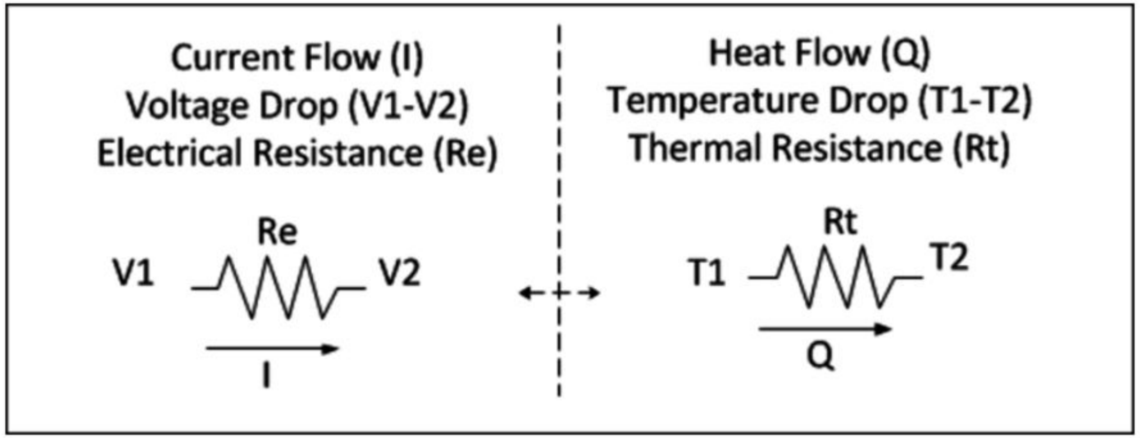
By Mohammadamin Hajikhodaverdian[1], Zihao Yuan[1], Sherief Reda[2] and Ayse K. Coskun[1]

[1]Boston University; [2]Brown University

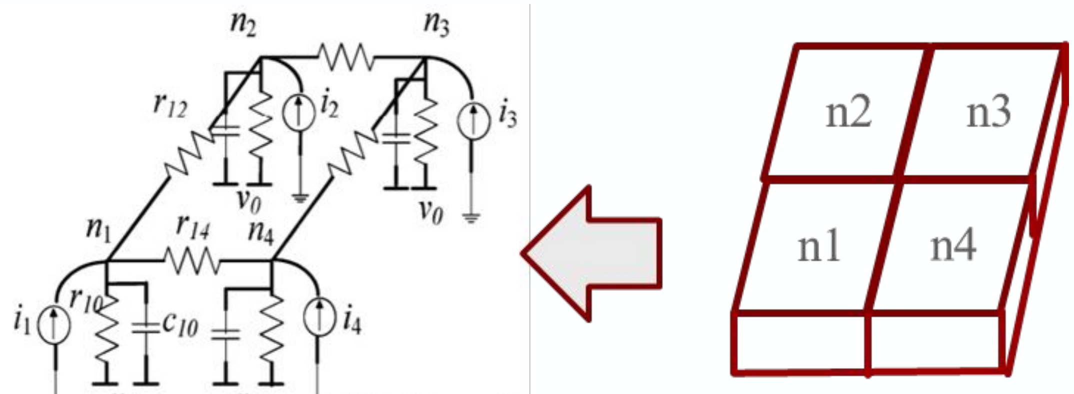
Workshop on Open-Source Design Automation (OSDA)
May 15, 2024

Compact Thermal Modeling (CTM)

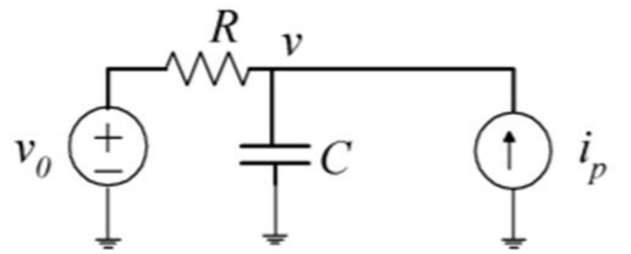
- Traditional thermal models
  - Finite element method (FEM)
  - Accurate but slow
- CTM
  - Fast and accurate modeling methodology
  - Duality between electric and thermal properties
  - Lump resistor-capacitor (RC) circuit
  - Chip can be modeled as a lump RC network



[S. Nazarian et al., IEEE'06]



[S. Nazarian et al., IEEE'06]

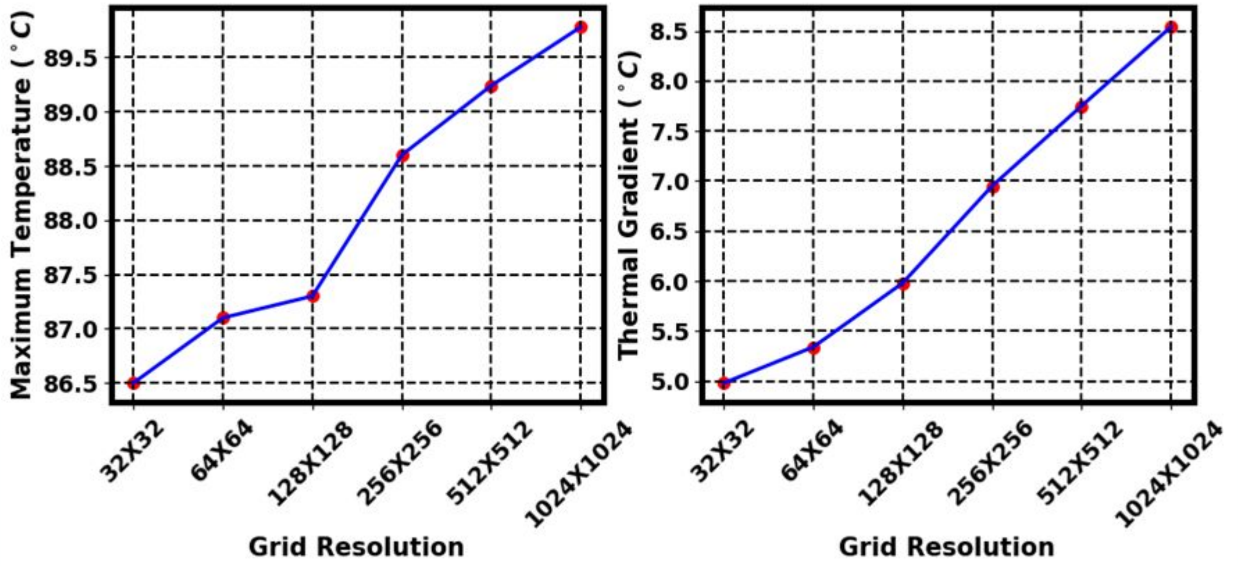


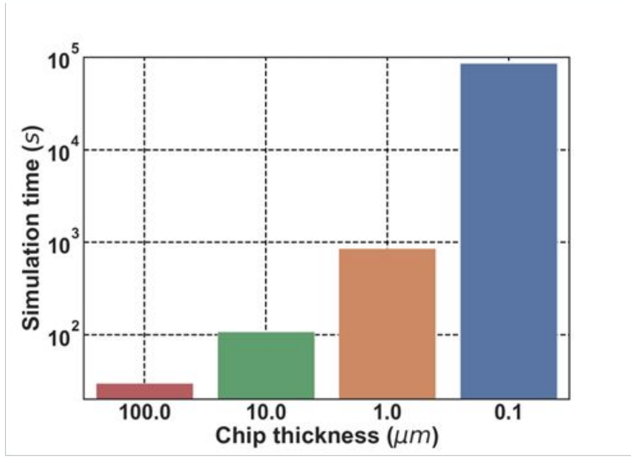
$$C\frac{dv}{dt} = \frac{v_0 - v}{R_E} + i_p$$

[S. Nazarian et al., IEEE'06]

Related Work

- Challenges in existing compact thermal simulators
  - Target architecture-level thermal simulations
    - HotSpot [K. Skadron et al., ISCA'10]
    - 3D-ICE [A. Sridhar et al., ICCAD'10]
  - Cannot tackle large and complex problems
    - Standard-cell designs
    - Monolithic 3D simulations
  - Hard to extend emerging integration and cooling technologies
    - New models for cooling methods frequently roll out customized software package





[Z. Yuan et al., TCAD'21]

Contributions of PACT

PACT: Parallel Compact Thermal Simulator

- Fast and accurate
- Standard-cell level to architecture-level
- High extensibility
- Interface to OpenROAD [T. Ajayi et al., DAC'19]
- Open-sourced simulator: https://github.com/peaclab
- VisualPACT

Accuracy vs. other thermal simulators:

- 3.28% vs. COMSOL
- < 0.5% vs. HotSpot
- 1.12℃ vs. 3D-ICE

Speed vs. HotSpot:

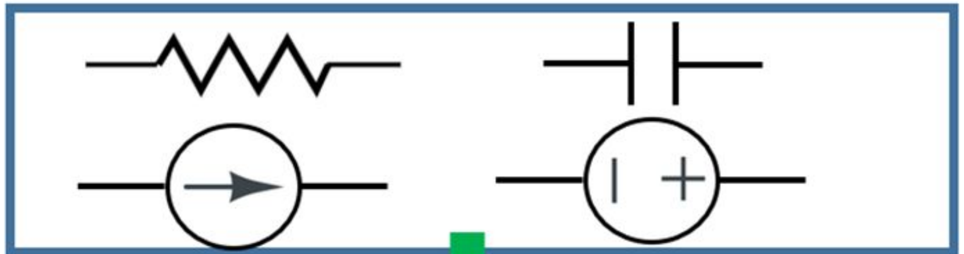
- Steady-state: 1.8X
- Transient: 186X

PACT Simulation Flow

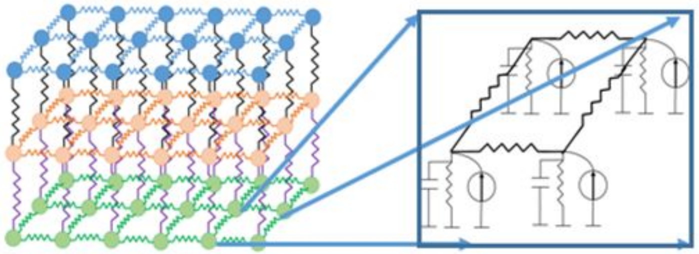
User inputs

- Chip stack descriptions
- # of grids and heat sink type
- Material properties and cooling method

Calculate netlist components



Thermal netlist generator



Simulation type and solver selection

- Steady-state (e.g., KLU, KSparse)
- Transient (e.g., Backward Euler, Trapezoidal)
- Options (e.g., time period, step size)

SPICE Engine

Parallel configuration (OpenMPI)

- # of Node, # of Cores
- Parallel option (e.g., -bind-to none)
- Job mapping option (e.g., -cpu-set)

Outputs

PACT Simulation Flow

User inputs

- Chip stack descriptions
- # of grids and heat sink type
- Material properties and cooling method

Symbol	Component name	Equivalent terminology in PACT
	Resistor	Thermal Resistor
	Capacitor	Thermal Capacitor
	Current source	Heat flow (power)
	Voltage-controlled current source	Liquid convection in microchannel grid
	Voltage source	Assign initial temperature and ambient temperature
	PWL current source	Enable transient thermal simulation with step response or real power traces

SPICE Engine

Outputs

Parallel configuration (OpenMPI)

- # of Node, # of Cores
- Parallel option (e.g., -bind-to none)
- Job mapping option (e.g., -cpu-set)

Simulation type and solver selection

- Steady-state (e.g., KLU, KSparse)
- Transient (e.g., Backward Euler, Trapezoidal)
- Options (e.g., time period, step size)

Extensibility of PACT

Liquid cooling input parameters

[Liq]
Thermal resistivity ((m-k)/w) = 1.647
Specific heat capacity (j/m^3k) = 4.181e6
inlet_temperature (Celsius) = 27
fluid_density (kg/m3) = 998
dynamic_viscosity (pa.s) = 8.89e-4
coolant_velocity (m/s) = 0.5
num_of_channels = 2

Liquid.py

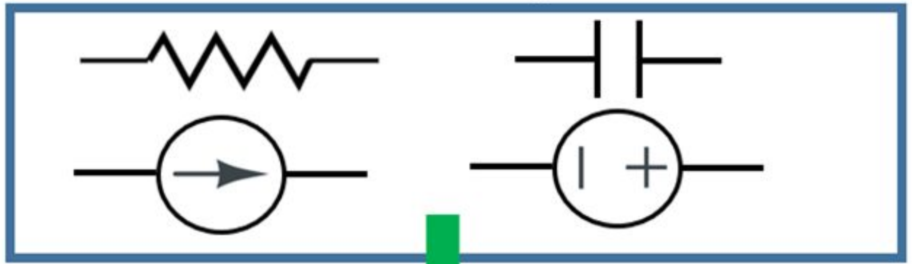
Liquid grid cell information

[Liq]
library_name = Liquid
library = Liquid.py
virtual_node = center_center

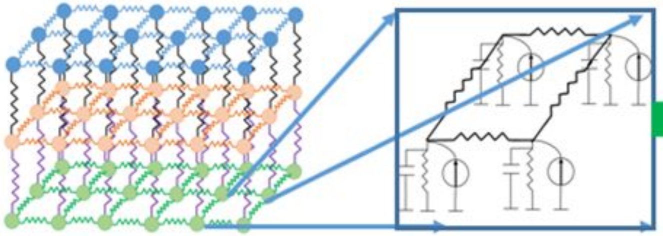
User inputs

- Chip stack descriptions
- # of grids and heat sink type
- Material properties and cooling method

Calculate netlist components



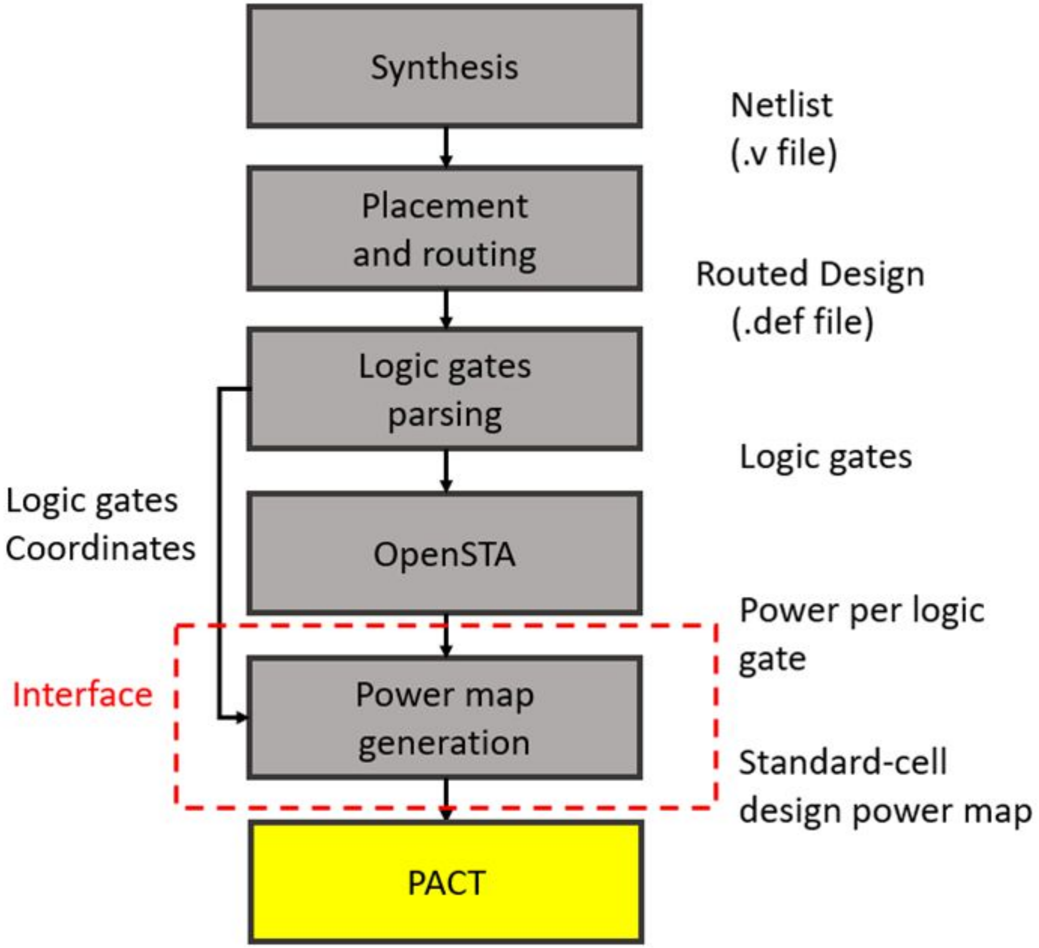
Thermal netlist generator



SPICE Engine

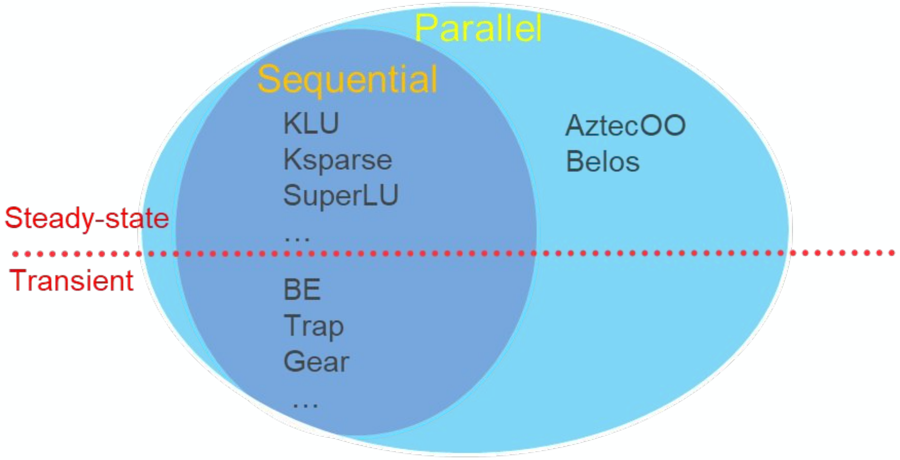
OpenROAD Interface and PACT Solvers

OpenROAD Interface



PACT Solvers

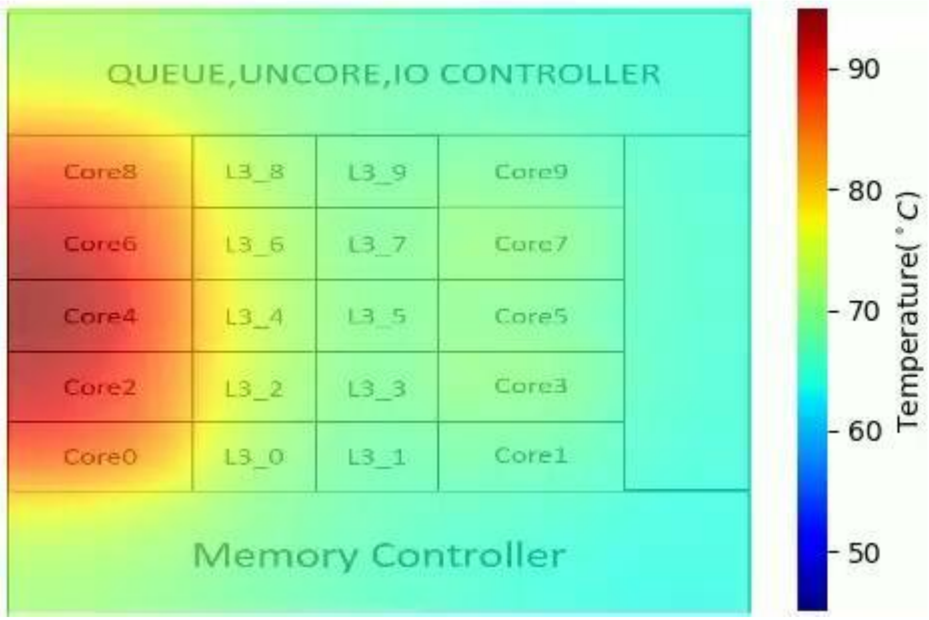
- Direct solver vs. Iterative solver
- Numerical instability issue with Forward Euler method (Monolithic 3D transient simulation)
- Simulation speed and accuracy tradeoff



VisualPACT

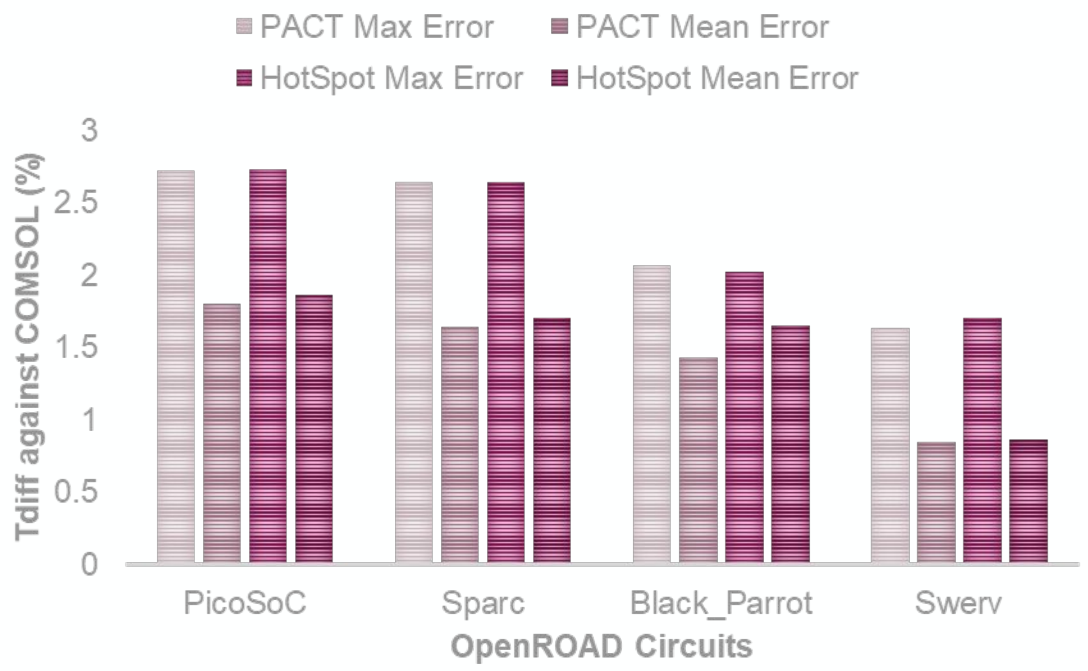
- VisualPACT
  - Generating thermal videos for transient thermal simulations
  - Visualizing transient thermal behaviors of architectural simulations

VisualPACT (Intel i7 6950X)



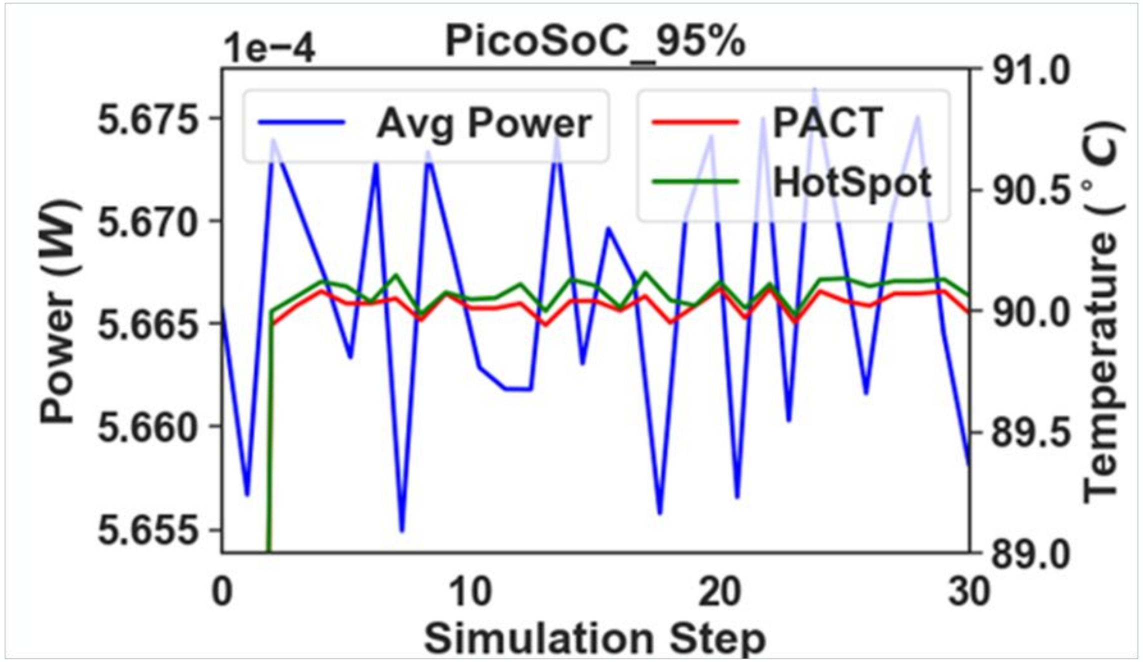
Validation with OpenROAD Benchmarks

Steady-State vs. HotSpot



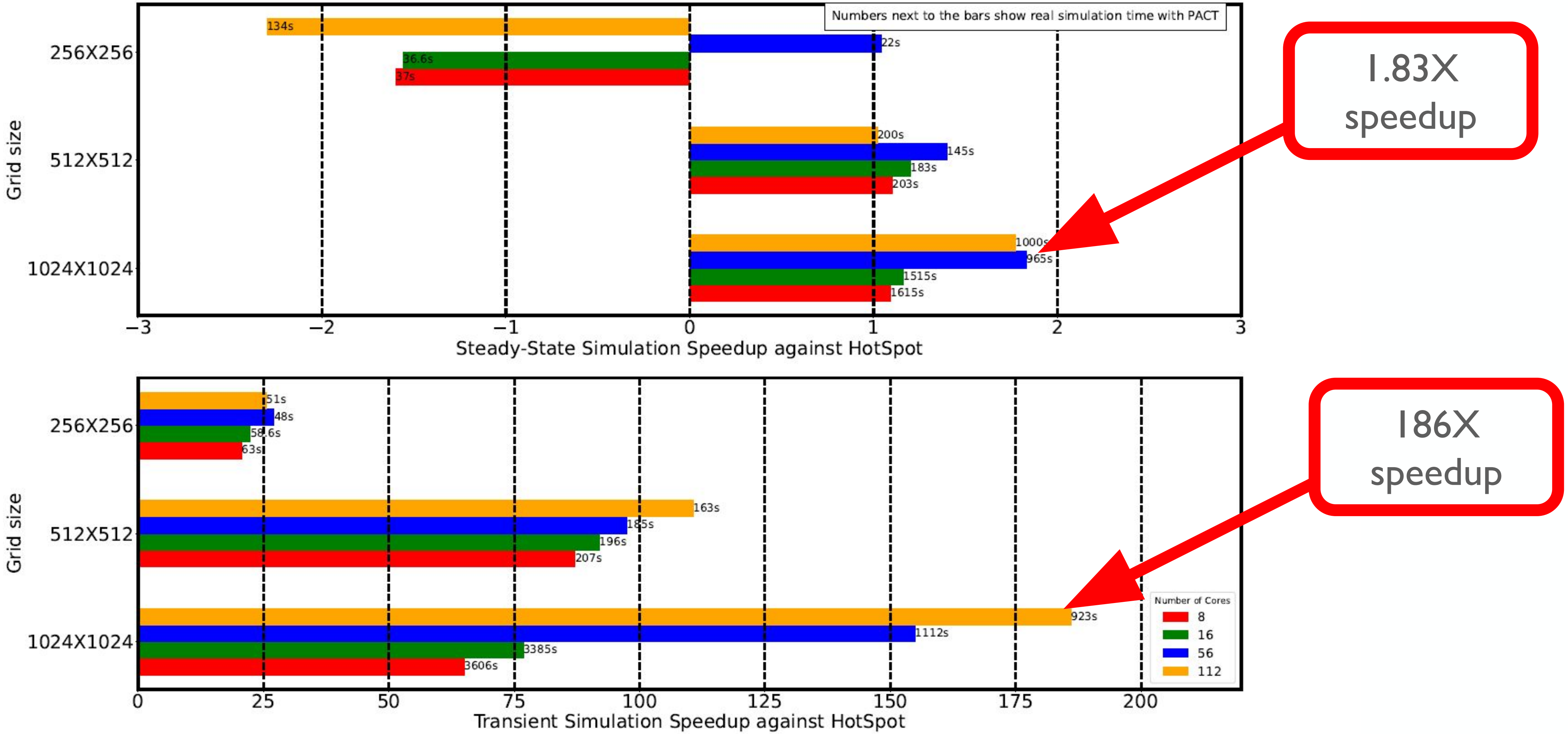
PACT vs. COMSOL (Max Steady-State Diff: 2.77%)

Transient vs. HotSpot



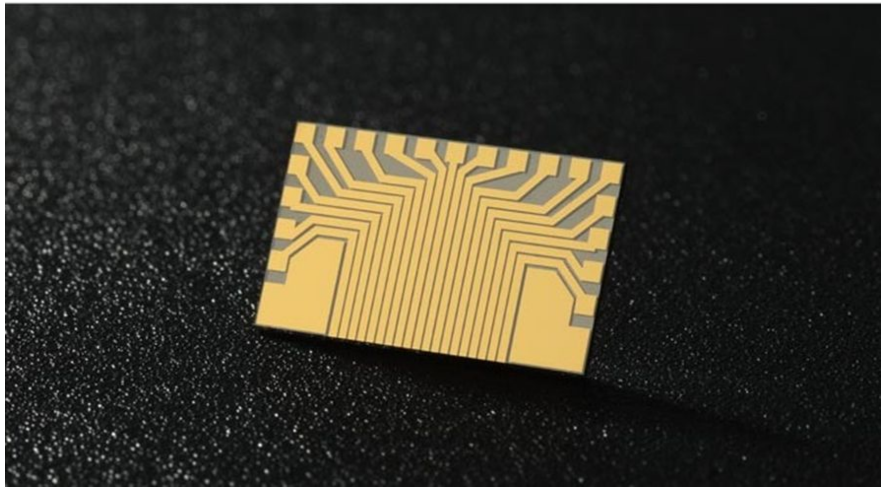
PACT vs. COMSOL (Max Transient Diff: 3.28%)

PACT Speed Analysis against HotSpot



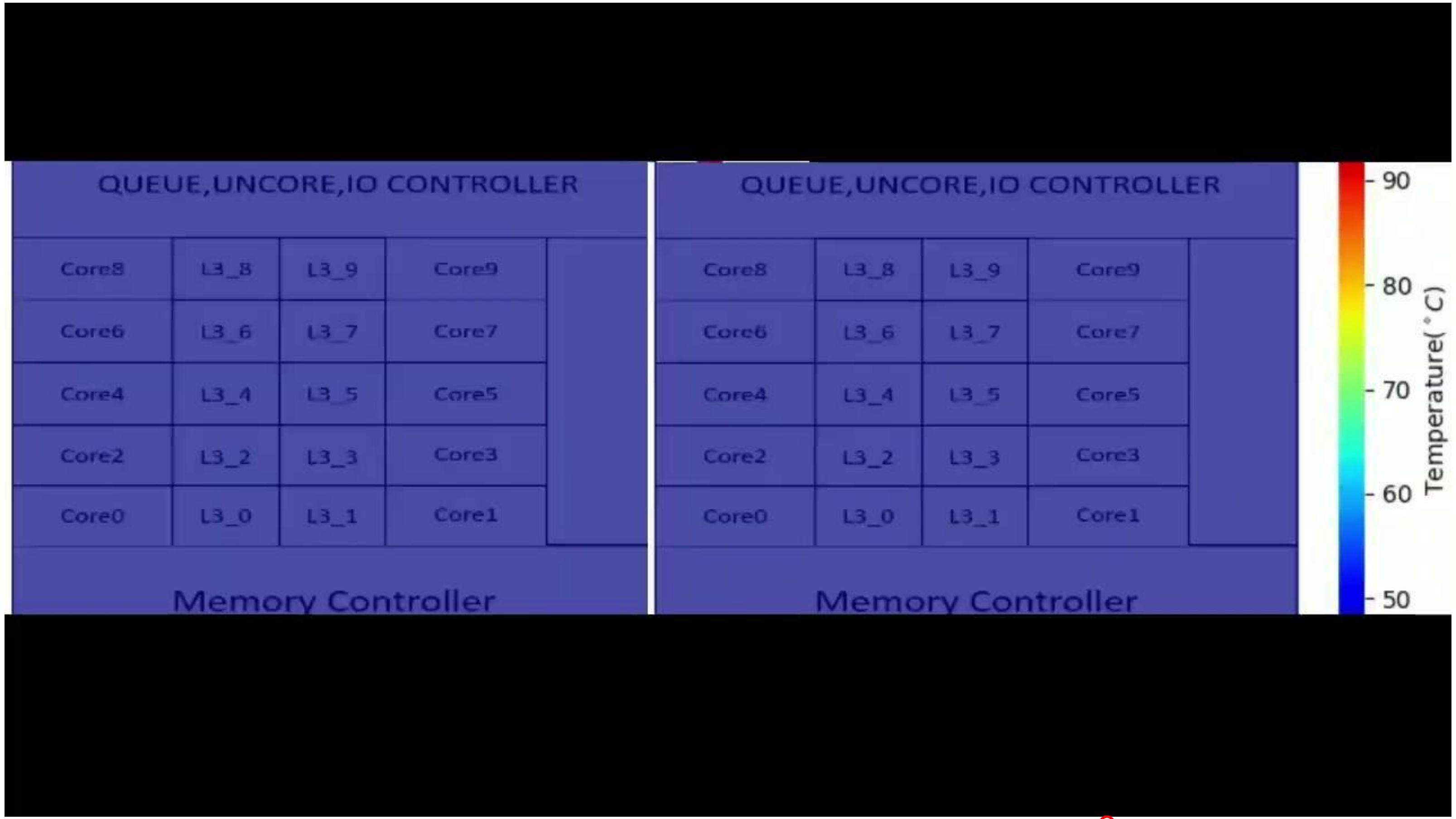
PACT Case Study: Lab-Grown Diamond Heat Spreaders

- High thermal conductance compared to the copper heat spreaders
- Can be bonded directly to the processor's layer w/o thermal interface
- Diamond heat spreaders vs. copper heat spreaders



PACT Case Study: Lab-Grown Diamond Heat Spreaders

Chip stack #1 (Copper)　　Chip stack #3 (Diamond)

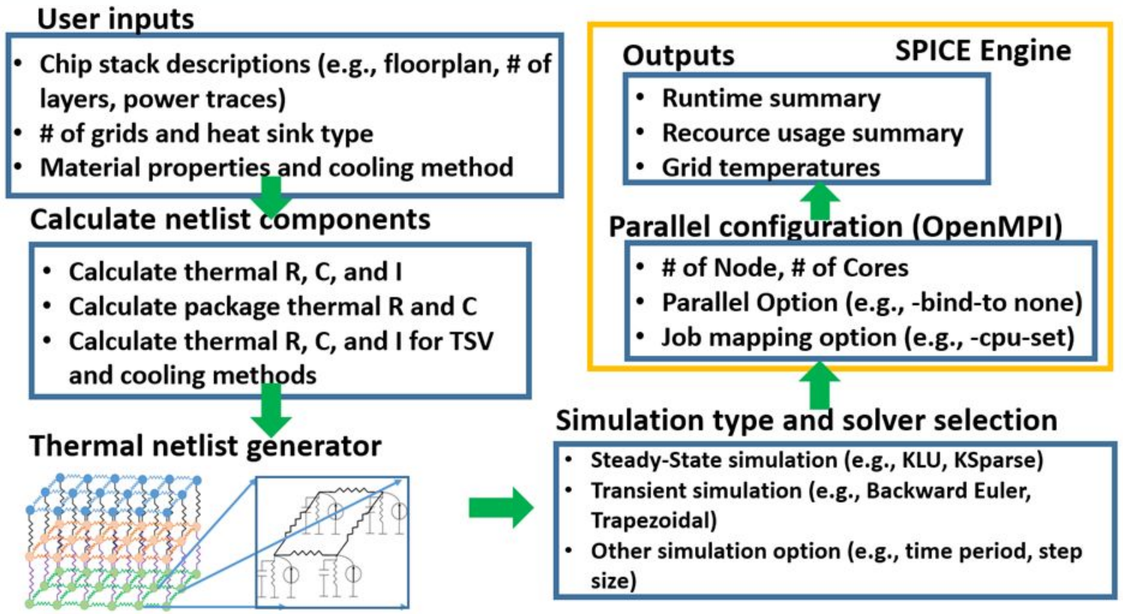


Hot Spot temperature reduction>20°C

PACT: Containerized Version

- Enable easy adoption without having to install dependencies (i.e., Xyce SPICE simulator)
- Use Docker to build a new image

- PACT
  - Fast and accurate parallel thermal simulator
  - Architecture level & standard-cell level
  - High extensibility for emerging cooling methods
  - Various numerical solvers
  - OpenROAD interface
  - VisualPACT



CONCLUDING REMARKS

More info at https://github.com/peaclab/PACT

Please send feedback to aminhaji@bu.edu