Two Fast Approaches for 3D Thermal Simulation of Integrated Circuits

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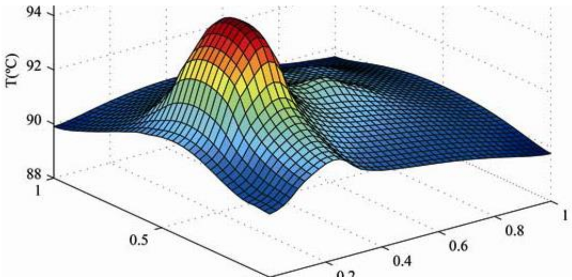
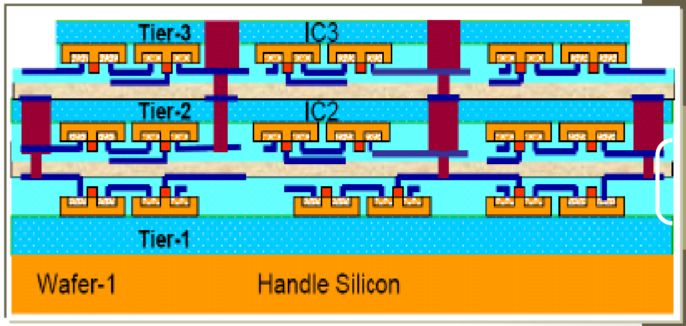
Outline

- Background
- 3D FVM for IC Thermal Simulation
- Domain Decomposition Techniques
- A Hybrid Random Walk Method
- Conclusions

Background

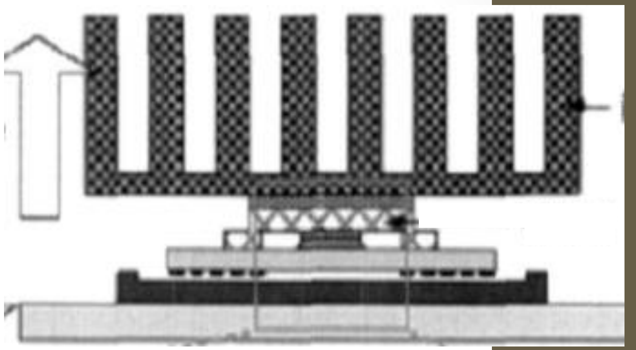
- Motivation of IC thermal analysis
  - The devices in an IC continuously increase
  - Heat dissipation and thermal management become problems threatening circuit reliability and performance
  - Chip-level thermal analysis (simulation): sign-off stage, also for design-time circuit optimizations
  - 3D IC is a trend: reduce delay, enable heterogeneous integration
  - Severe heat dissipation problem
  - Importance of accurate thermal simulation during design



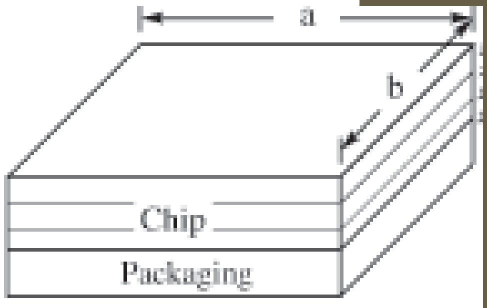


Background

- Chip-level thermal simulation
  - Should consider heat sink components
  - Simulating the whole IC thermal model (w/ irregular geometry) brings *computational challenges*



- Existing works
  - 1.Consider simplified rectangular domain
  - [Li, ICCAD’04]: Geometric multigrid iterative
  - [Zhan, TCAD’07]: Green’s function based
  - 2.Consider realistic pyramid-geometry domain
  - [Heriz, Thermal’07]: Convolution based, only for <u>low-resolution</u>
  - [Qian, ICCAD’10-TODAES’12]: Fast Poisson solver (FPS)+PCG, with <u>increased unknowns</u> and geometry-dependent <u>convergence</u>



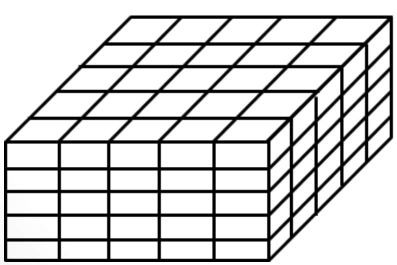
cause > 10°C error !

3D FVM for Thermal Simulation

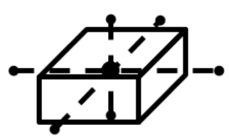
- Problem formulation
  - 3D steady-state heat equation

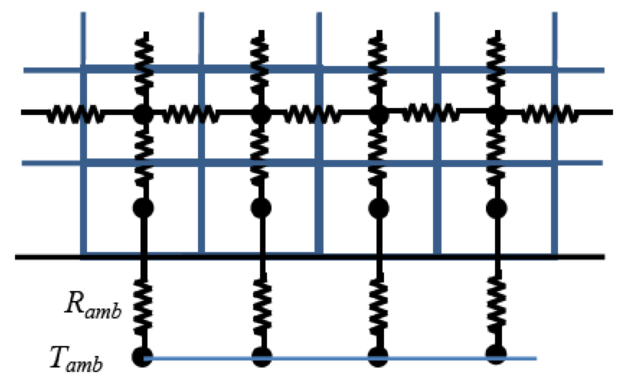
$$k \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2} \right) = -p(x,y,z)$$

  - Boundary conditions: Neumann (adiabatic) condition, convective condition $k \dfrac{\partial T}{\partial \vec{n}} + h(T - T_{amb}) = 0$
  - Finite difference (volume) discretization



Thermal resistor!

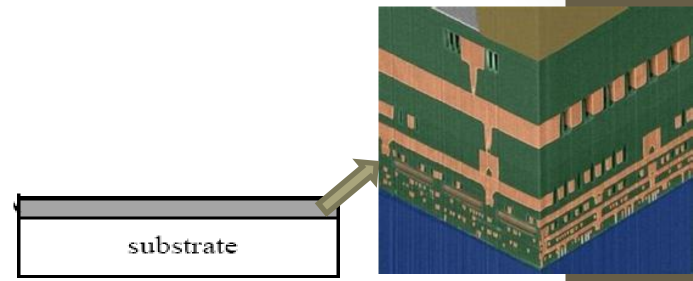




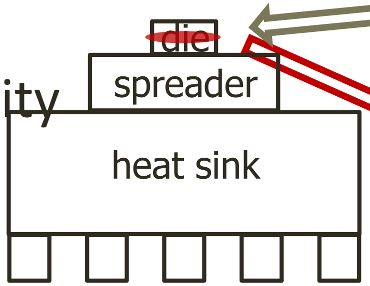
3D FVM for Thermal Simulation

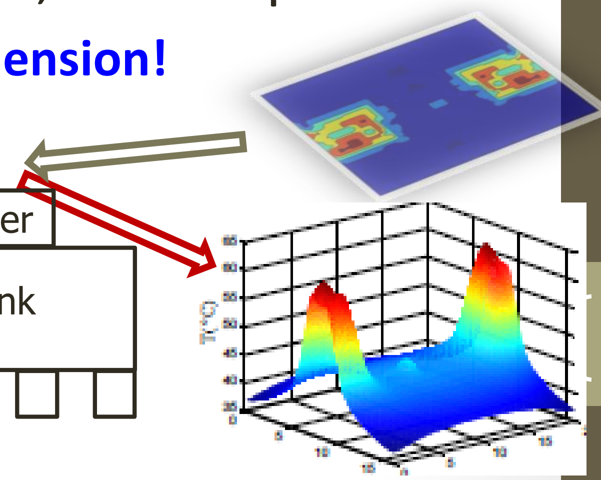
- Practical considerations
  - Inhomogeneous material in IC region
  - Thermal resistors across various material interfaces
  - To simplify, approximate the interconnect layer with a homogeneous layer

$$k_{eff} = r_{metal} \cdot k_{cooper} + (1 - r_{metal}) \cdot k_{oxide}$$



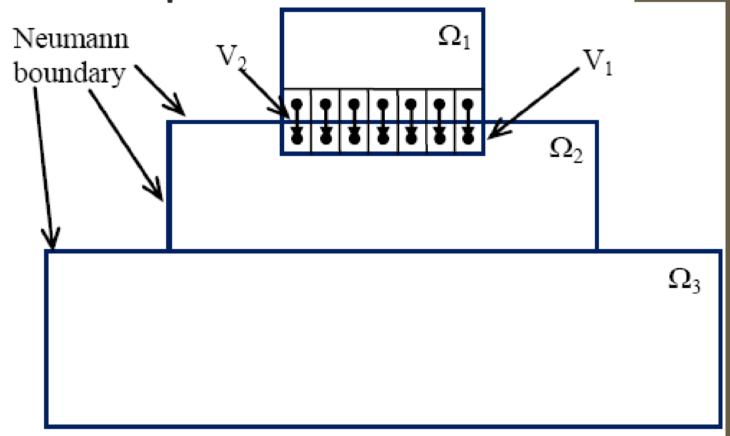
  - Power source resembles current source; solve equivalent circuit equation: $AT = f$ **Huge dimension!**
  - Two observations
    - Subdomain geometry regularity
    - Concern only the die region





Domain Decomposition Technique

- A general method for simulating complex domain
  - Nonoverlapping DDM from FVM-circuit viewpoint
    - The solution of Ω_2 provides Dirichlet boundary condition for Ω_1
    - The heat flow at the bottom of Ω_1 provides Neumann condition for Ω_2
  - Different iteration schemes
    - Top-to-bottom order
    - Bottom-to-top order
    - Middle-to-end order
    - End-to-middle order
    - Nested two-subdomain order (more reliable but costly)

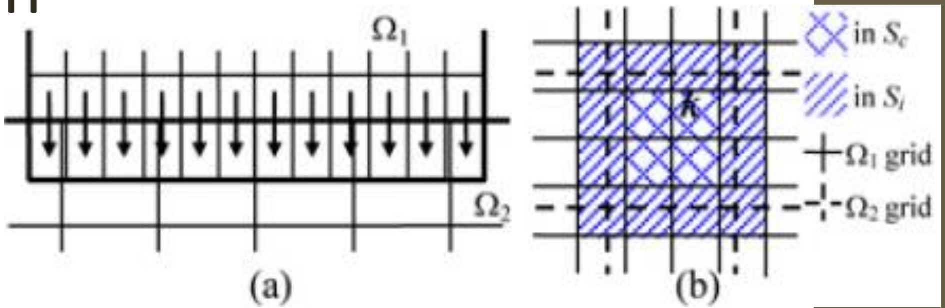


- Check convergence w/ the interfacial quantities
- Relaxed iterative scheme:

$$T_{V1}^{(i+1)} = T_{V1}^{(i)} + \omega(\tilde{T}_{V1}^{(i+1)} - T_{V1}^{(i)})$$

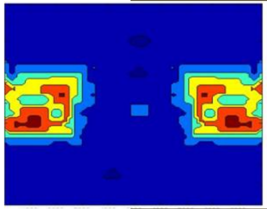
Domain Decomposition Technique

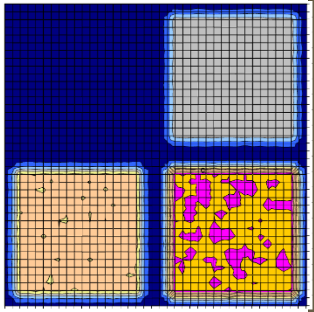
- Nonconformal discretization
  - Solve subdomains separately
  - Much coarser discretization used for heat spreader/sink



  - Linear interpolation converting quantities across interface; less affects the temperature in IC subdomain
- Exploit the regularity of subdomain
  - With conductivity homogenization, most subdomains are rectangular ones with simple configurations and conditions
  - FPS [Qian, ICCAD’10] with O(nlogn) time-complexity and O(n) space-complexity used for solving subdomains

Domain Decomposition Technique



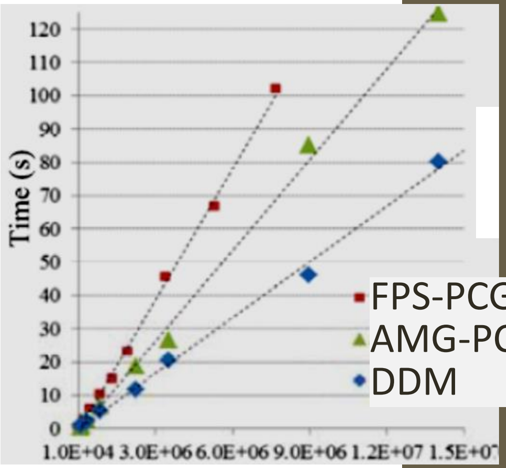


- Test cases
  - Case 1: A 2D chip imitating the Power6 (175W in 1.6x2 die)
  - Case 2: A 4-core 2D chip (176W in 1x1 die)
  - Case 3: A 3D chip with Case 1+ 2 SRAM dies
- Experiments
  - Apply conformal discretization, and compare with Matlab "\", ICT-PCG, AMG-PCG (the fastest iterative PG solver), and FPS-PCG
  - With the result of Matlab "\", check accuracy
  - Apply nonconformal discretization, to show efficiency improvement
  - Use the simulator in heat sink component design

Domain Decomposition Technique

Matrix	n	"\"	ICT-PCG		AMG-PCG			DDM	
		Time(s)	Iter.	Time(s)	Iter.	Time(s)	Mem.	Time(s)	Mem.
M1-1	1.45e5	**35.4**	75	**16.7**	16	**1.15**	14MB	**1.20**	< 8MB
M1-2	1.51e5	**38.9**	75	**16.8**	13	**1.01**	33MB	**1.28**	< 8MB
M1-3	3.42e5	**331.5**	110	**43.1**	14	**2.63**	72MB	**2.48**	< 8MB
M1-4	5.47e6	--	--	--	15	**51.1**	1.1GB	**32.3**	80MB
M1-5	1.51e7	--	--	--	14	**142.6**	3.0GB	**90.7**	218MB
M1-6	3.42e7	--	--	--	--	--	--	**207.2**	494MB
M2-1	8.97e4	**18.4**	66	**6.88**	12	**0.52**	14MB	**0.82**	< 10MB
M2-2	1.40e5	**43.4**	78	**16.7**	12	**0.89**	31MB	**1.13**	< 10MB
M3-3	3.59e5	**359.3**	103	**204.9**	12	**2.68**	78MB	**2.21**	< 10MB
M2-4	3.51e6	--	--	--	12	**26.63**	718MB	**20.5**	55MB
M2-5	1.40e7	--	--	--	13	**124.6**	2.8GB	**80.1**	217MB
M2-6	3.31e7	--	--	--	--	--	--	**185.2**	493MB
M3-1	1.50e5	**39.6**	77	**16.8**	13	**1.08**	18MB	**1.28**	< 8MB
M3-2	1.55e5	**40.8**	77	**16.9**	13	**1.11**	37MB	**1.32**	< 8MB
M3-3	3.46e5	**493.4**	112	**33.3**	14	**2.81**	78MB	**2.61**	< 8MB
M3-4	5.54e6	--	--	--	14	**49.1**	1.1GB	**33.5**	80MB
M3-5	1.55e7	--	--	--	15	**160.8**	3.1GB	**92.4**	218MB
M3-6	3.46e7	--	--	--	--	--	--	**209.1**	494MB

- >10X memory save!
- Faster than iterative solvers for large case
- Converge in 8, 9 steps



- The temperature error in IC region is less than 0.01 °C

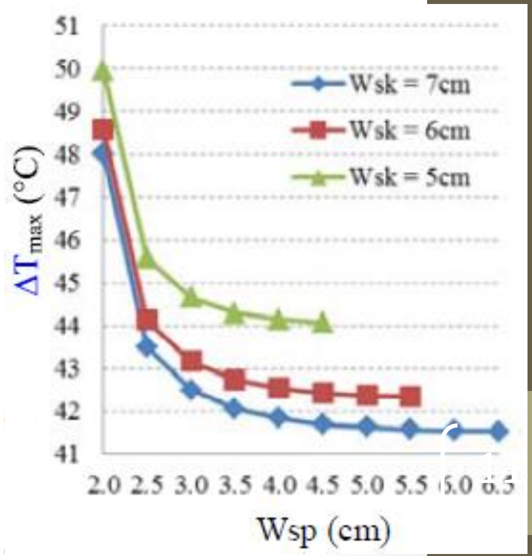
Domain Decomposition Technique

- Nonconformal discretization

Matrix	Conformal grid			Non-conformal grid				
	n	Time(s)	T_{max}(°C)	n	Time(s)	T_{max}(°C)	Err_{max}(°C)	Speedup
M1-4	5.47e6	32.3	61.89	5.73e5	3.86	61.90	0.11	**8.4**
M1-5	1.51e7	90.7	61.97	1.65e6	8.98	61.95	0.03	**10.1**
M1-6	3.42e7	203.2	61.88	1.99e6	11.2	61.85	0.04	**18**
M1-10	5.41e7	310.1	61.85	3.22e6	18.5	61.84	0.02	**17**

- Apply to larger case
- < 0.05 °C Error on hot spot
- >10X memory save

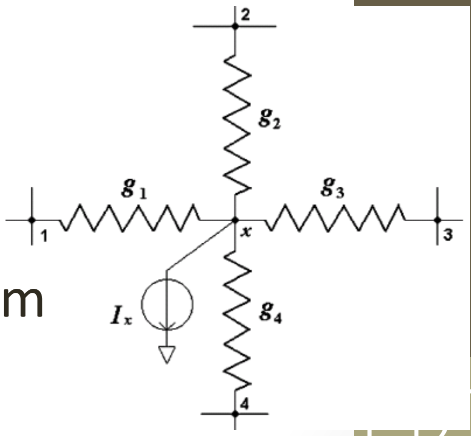
- High-resolution simulation and design
  - 1.05×10^7 unknown (50μm discretization-step) in IC region, needs 72s simulation time
  - Study the temperature variations with the widths of heat spreader/sink changed
  - 24-configuration simulation costs 7 mins.



A Hybrid Random Walk Method

- Thermal simulation for hot-spots at device layer
  - Entire temperature profile is often not required
- Random walk method for thermal analysis
  - Equivalent to the P/G analysis problem, w/ thermal resistors
  - P/G Random walk methods [Qian, TCAD'05][Miyakawa, GLSVLSI'11]
  - [Wong, DATE'06]: used for thermal via planning in 3D IC

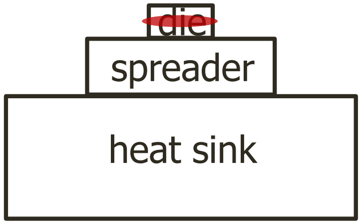
$$V_x = \sum \frac{g_i}{\sum g_i} V_i - \frac{I_x}{\sum g_i}$$

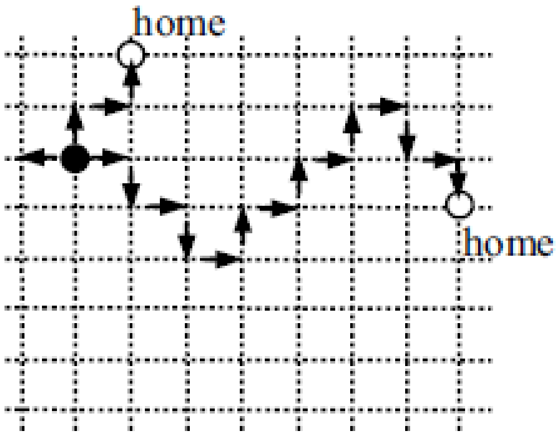


  - Drawbacks of existing works
    - Not consider characteristics of IC thermal problem (boundary condition, geometry features)
    - The computational speed is very slow

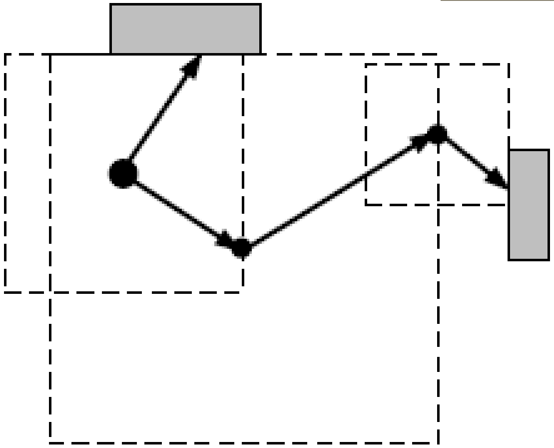
A Hybrid Random Walk Method

- Main ideas
  - Heat sink components (e.g. Pyramid-shape)
  - Slow speed of RW (called GRW) is due to the long length of a walk path
  - Another RW (FRW) is able to reduce the length of a walk path
  - FRW encounters difficulty if there are the *source item* and *Neumann, convective boundary condition*





Generic random walk

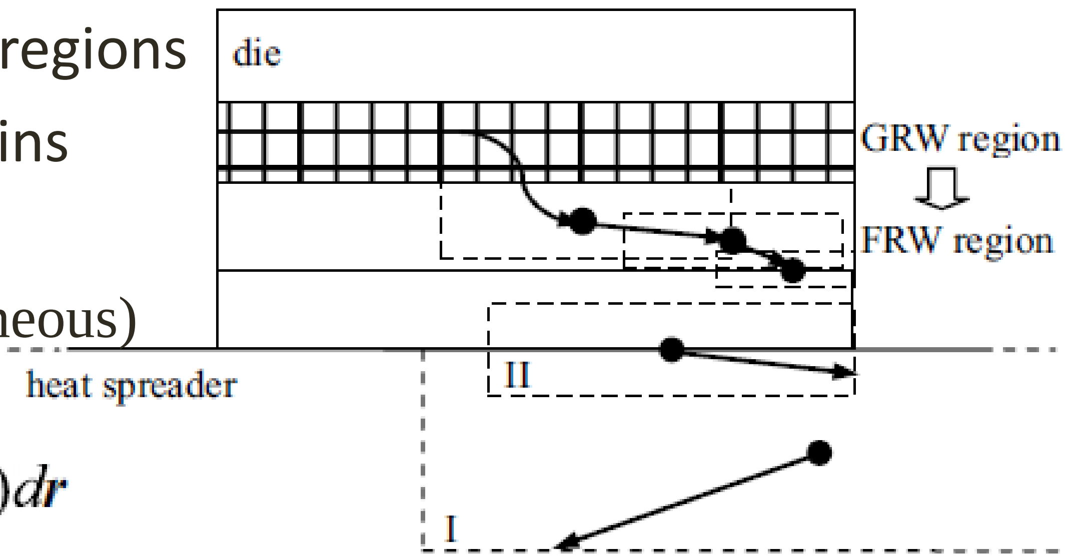


Floating random walk

Can We Combine Them?

A Hybrid Random Walk Method

- GRW+FRW
  - Perform FRW in simple regions
  - *Cuboid* transition domains
    - I (homogeneous)
    - II (half &half homogeneous)
  - FRW transition



$$T_c = \oint_S G_s(\boldsymbol{r}) T(\boldsymbol{r}) d\boldsymbol{r}$$

  - Pre-characterize the transition domains with a hop-target table
  - Neumann boundary: path reflection / special transition domain
  - Convective boundary: Large $\boldsymbol{R_{amb}}$ barriers GRW hop; convective-specific transition domain

A Hybrid Random Walk Method

- Test cases
  - Case 1: A 4-core 2D chip (176W in 1x1 die)
  - Case 2: A 2D chip imitating the Power6 (175W in 1.6x2 die)
- Experimental results
  - Hybrid0: GRW+FRW; Hybrid1: Neumann boundary treatment; Hybrid2: convective boundary treatment (1% 1-σ error)

Average runtime for calculating the temperature of a node (s)

Test case	#node	GRW			Hybrid random walk				
		time	#walk	#hop	hybrid0	hybrid1	hybrid2	#hop	Sp*
1-1	5.24e5	49.8	5471	2.34e5	25.6	23.5	2.76	8.77e3	18
1-2	4.19e6	199	5522	9.28e5	44.8	33.3	4.12	8.13e3	48
1-3	6.55e7	949	6409	5.64e6	54.1	38.8	3.64	7.52e3	261
2-1	5.33e5	35.5	3576	2.52e5	30.1	25.0	1.26	1.05e4	28
2-2	4.26e6	143	3709	9.90e5	41.5	37.6	2.85	1.79e4	50
2-3	6.66e7	762	3281	5.98e6	72.7	48.1	5.17	3.12e4	147

A Hybrid Random Walk Method

- Experimental results
  - Memory overhead: ~81MB for transition-domain characterization
  - The pre-characterization runs only once for same chip structure or chips manufactured by same materials
  - Accuracy validated by Matlab “\”
  - How the aspect ratio of the cuboid transition domain in FRW affects the efficiency of the proposed hybrid method ?

Average Hybrid1’s runtime for calculating a node’s temperature (s)

Aspect ratio	1	5	8	10	12	15	20
Time/node	170	43.3	41.9	41.3	40.9	41.8	42.5

  - Choosing cuboid transition domain (a.r.=10) brings 4.1X speedup

Conclusions

- Domain decomposition method
  - Make the fast thermal solvers workable while appreciating the effect of heat sink components
  - Can beat iterative equation solver for large case
  - Nonconformal discretization grid reduces the computation with negligible loss of accuracy
- Hybrid random walk method
  - Combining GRW and FRW brings one or two orders of magnitude speedup, with some memory overhead
  - Suitable for the scenarios where only the temperature of some local hot-spots is needed

Thanks !