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Printing in a JIFFY

A Parallel-in-Time Heat Transfer Solver for Additive Manufacturing

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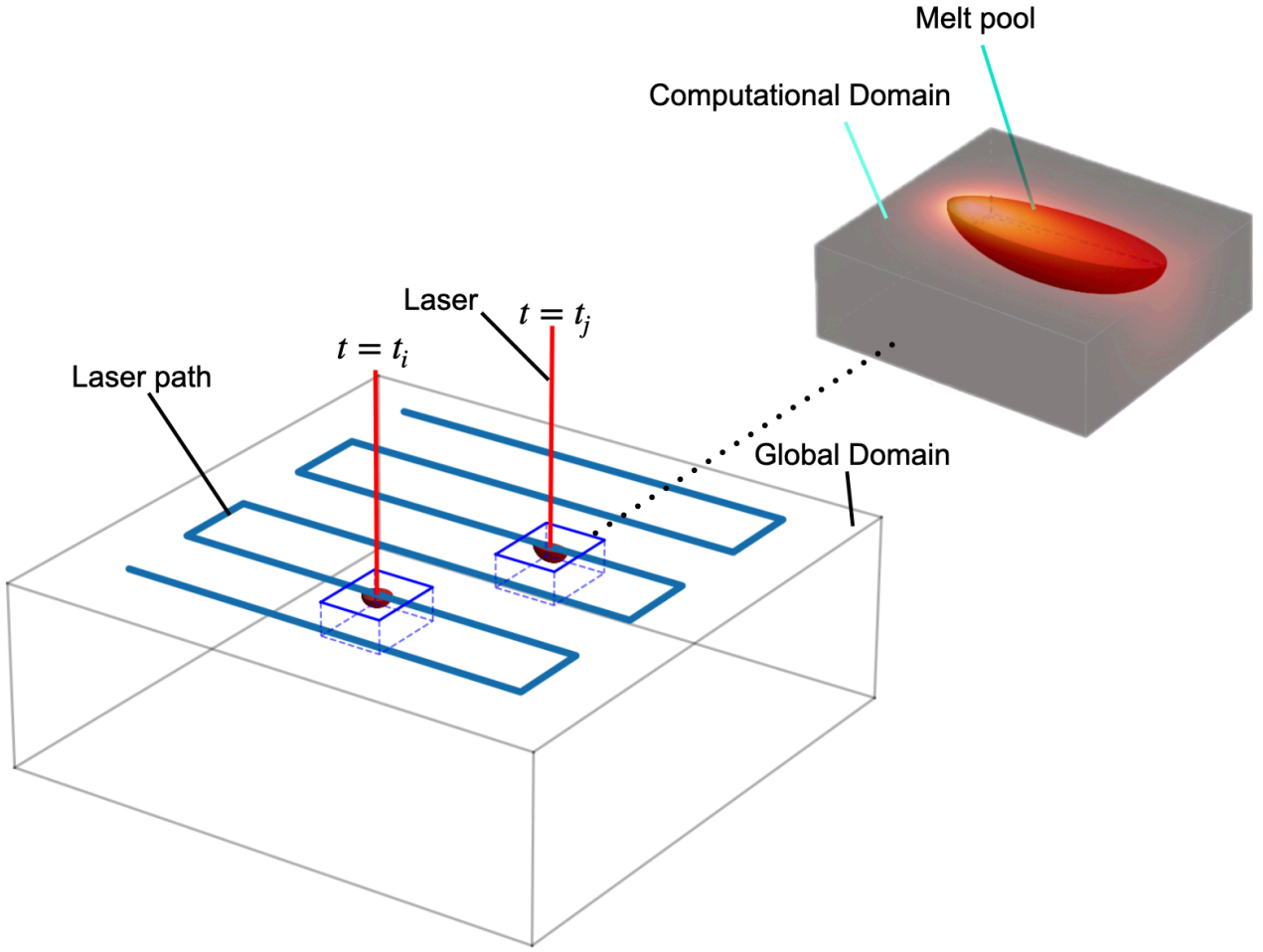
Problem statement

$$\frac{\partial u}{\partial t} = \Delta u + f_{\text{laser}}$$

$$\frac{\partial u}{\partial n} = -q_{\text{conv}} - q_{\text{rad}} \quad \text{on } \Gamma_{\text{top}}$$

$$\frac{\partial u}{\partial n} = 0 \quad \text{on } \partial\Omega \backslash \Gamma_{\text{top}}$$

$$u(\mathbf{x},0) = u_{\text{ambient}} \quad \text{in } \Omega$$

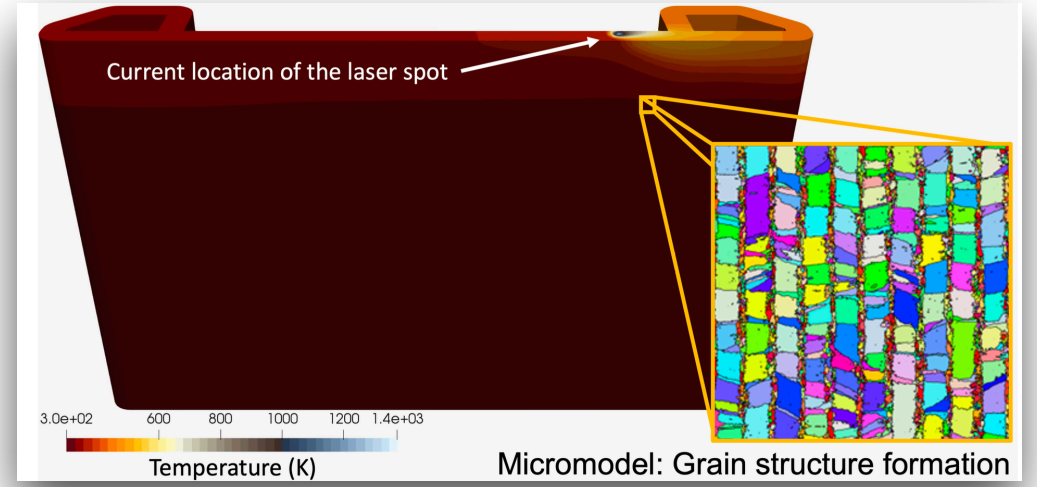


Parts: $O(10)cm$ **, Melt pool:** $O(100)\mu m$

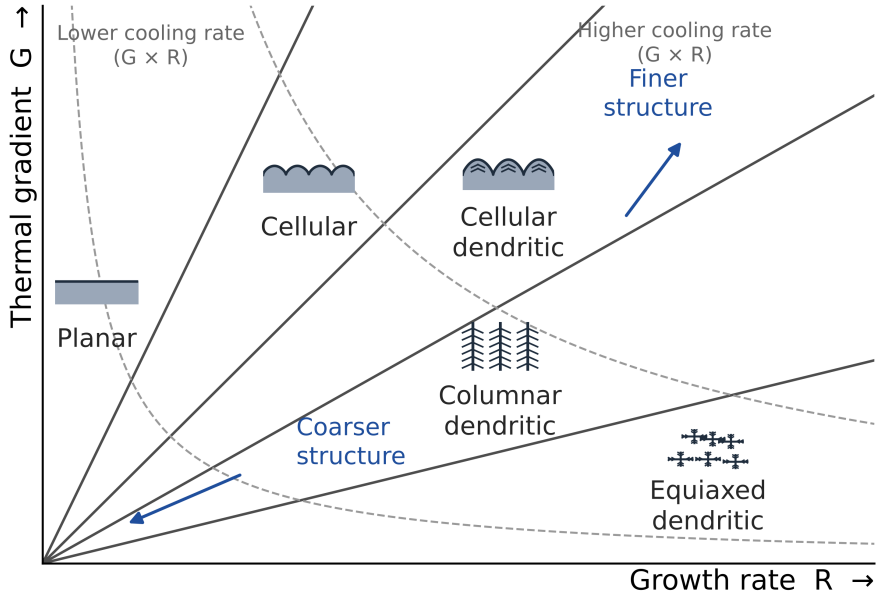
A 15-layer, 5 cm × 5 cm part needs **3.27M time steps × 9M points each**

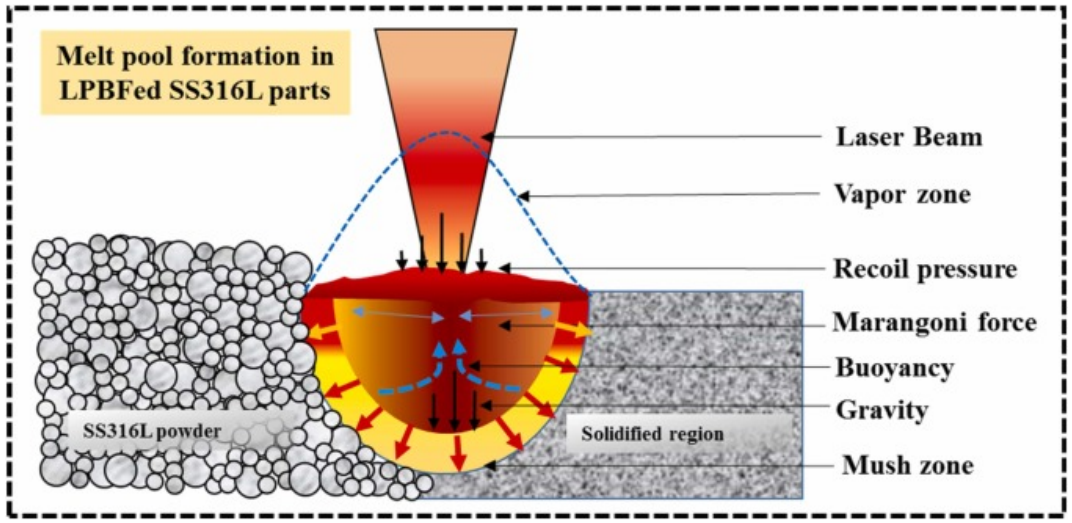
Takes **> 1 day** on a fast solver such as HERMES (one H100); Bottleneck: **sequential in time**

Target application: additive manufacturing

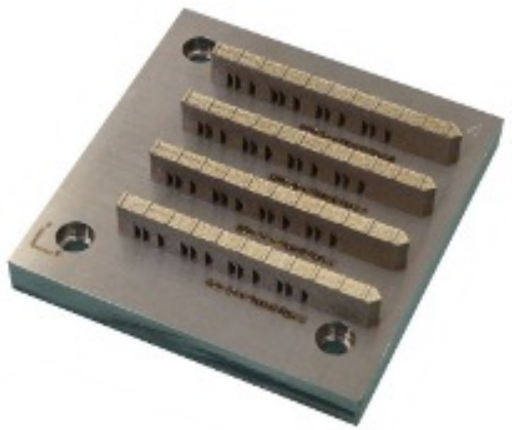


Web





Web

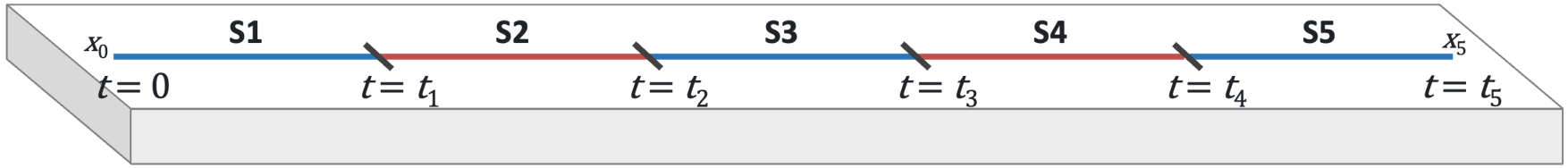


NIST AM Bench test build



Aerospace: GRCop-42 rocket combustion chamber

Segment partition along laser path



Sequential:

$\dot{u}_1 = \Delta u_1 + f_1$, $u_1(0) = 0$ → $\dot{u}_2 = \Delta u_2 + f_2$, $u_2(t_1) = u_1(t_1)$ → $\dot{u}_3 = \Delta u_3 + f_3$, $u_3(t_2) = u_2(t_2)$ → $\dot{u}_4 = \Delta u_4 + f_4$, $u_4(t_3) = u_3(t_3)$ → $\dot{u}_5 = \Delta u_5 + f_5$, $u_5(t_4) = u_4(t_4)$

Parallel:

Base simulation: $\dot{u}^* = \Delta u^* + f$

$u_1^*(0) = 0$ | $u_2^*(t_1) = 0$ | $u_3^*(t_2) = 0$ | $u_4^*(t_3) = 0$ | $u_5^*(t_4) = 0$

Correction 1: $\dot{v} = \Delta v$

$v_{1\to2}(t_1) = u_1^*(t_1)$ | $v_{2\to3}(t_2) = u_2^*(t_2)$ | $v_{3\to4}(t_3) = u_3^*(t_3)$ | $v_{4\to5}(t_4) = u_4^*(t_4)$

Correction 2:

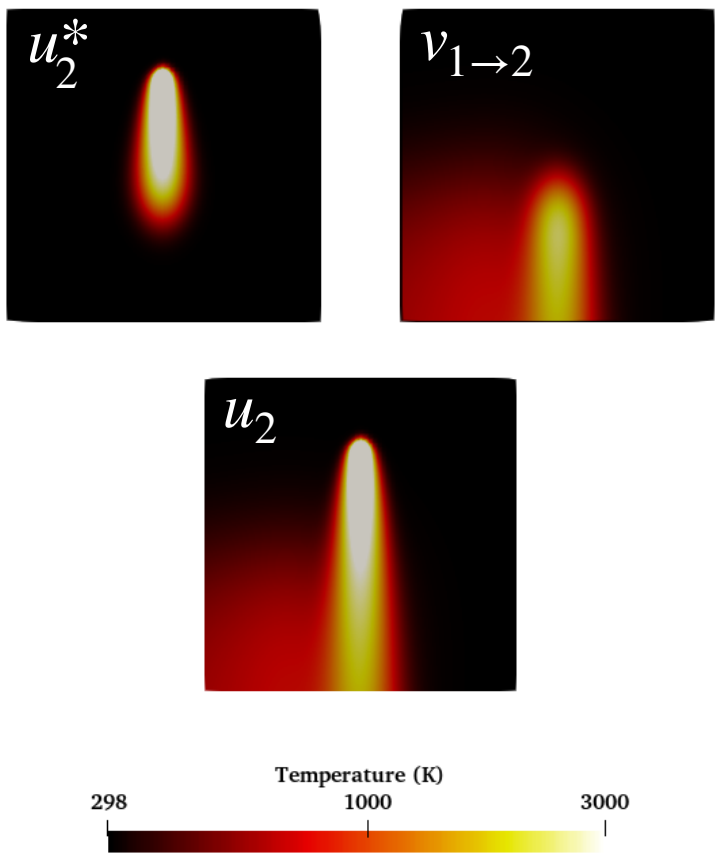
$v_{1\to3}(t_2) = v_{1\to2}(t_2)$ | $v_{2\to4}(t_3) = v_{2\to3}(t_3)$ | $v_{3\to5}(t_4) = v_{3\to4}(t_4)$

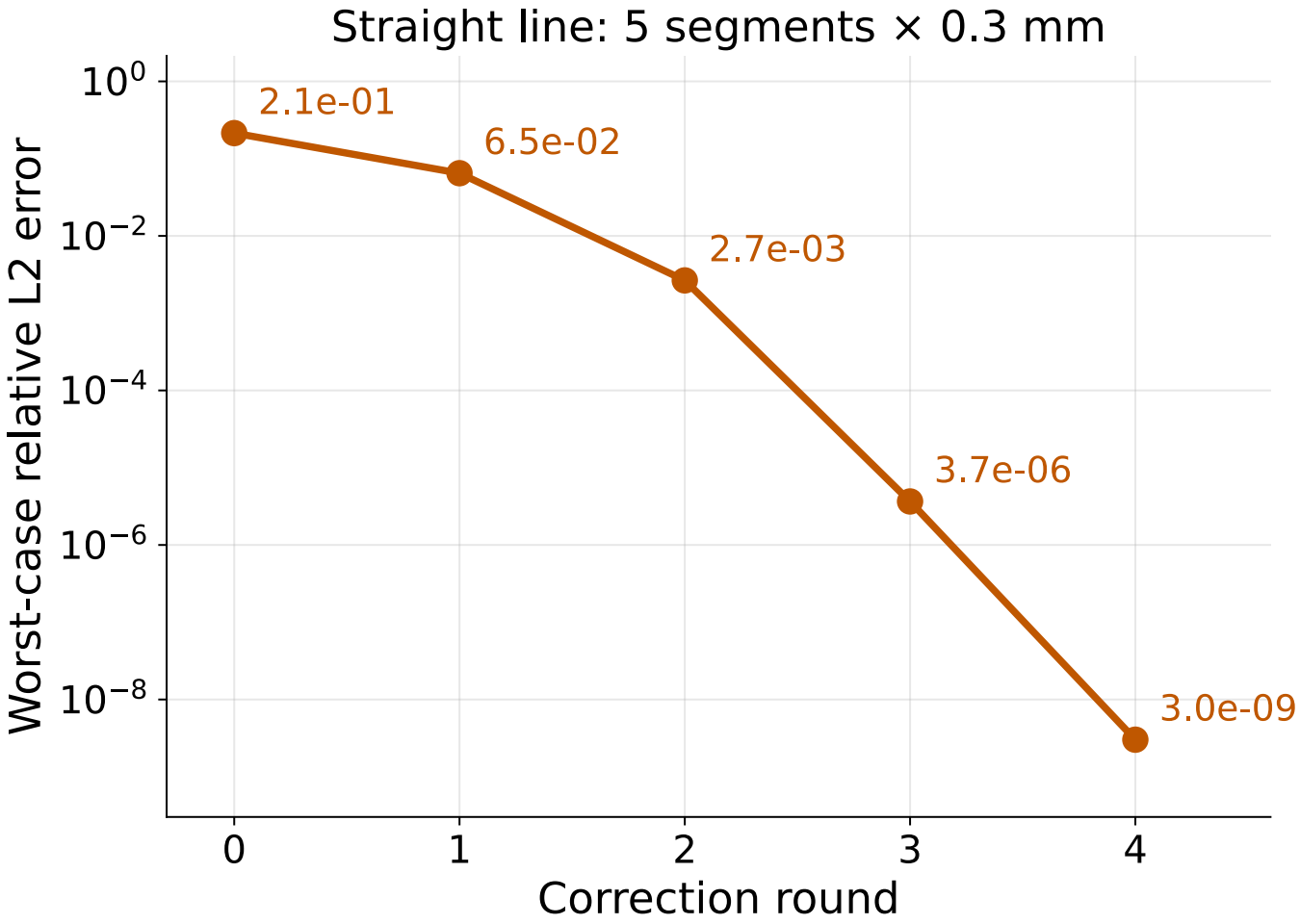
Correction 3:

$v_{1\to4}(t_3) = v_{1\to3}(t_3)$ | $v_{2\to5}(t_4) = v_{2\to4}(t_4)$

Correction 4:

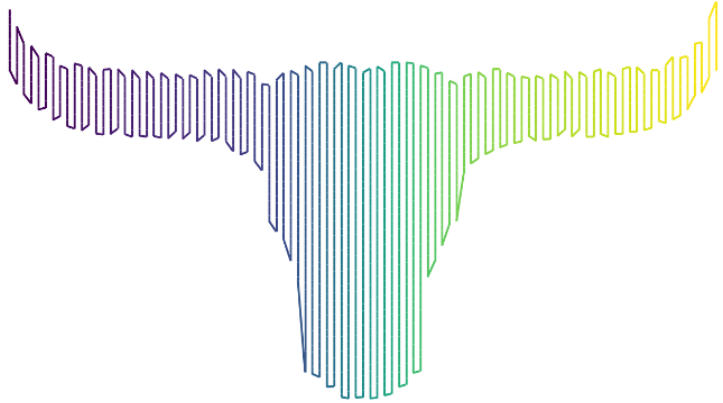
$v_{1\to5}(t_4) = v_{1\to4}(t_4)$


u_2^*
$v_{1\to2}$
u_2
Temperature (K)
298
1000
3000

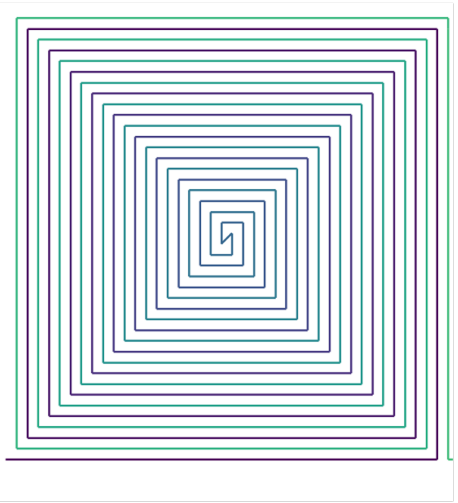

Straight line: 5 segments × 0.3 mm
Worst-case relative L2 error
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
2.1e-01
6.5e-02
2.7e-03
3.7e-06
3.0e-09
0
1
2
3
4
Correction round

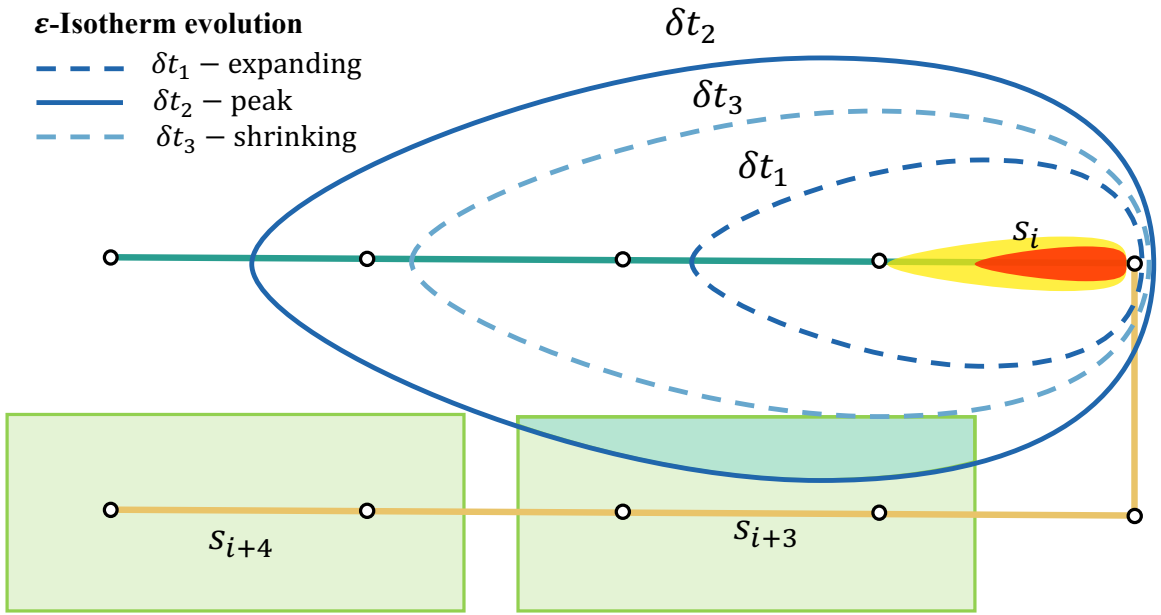
Dependency-DAG construction on complex paths

Raster:



Spiral:





$$\Delta T(d,\tau) \propto \tau^{-3/2} \exp\left(-\frac{d^2}{4\alpha\tau}\right)$$

Closed-form ΔT from distance d and delay τ between segments

$G = (V, E)$

Node $s_i \in V$: one scan segment

Edge (s_i, s_j), $i < j$

$$\tau_{ij} = t_{j-1} - t_i$$

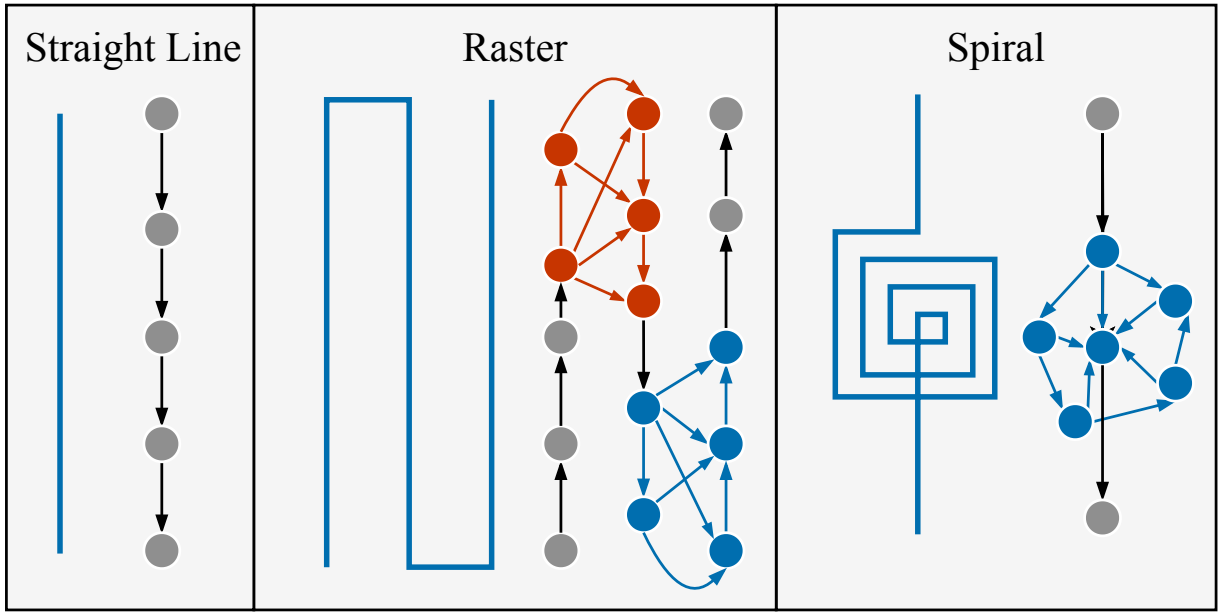
elapsed time from s_i to s_j

$$d_{ij} = \min \|x - y\|, \quad x \in s_i, y \in s_j$$

closest distance between the two segments

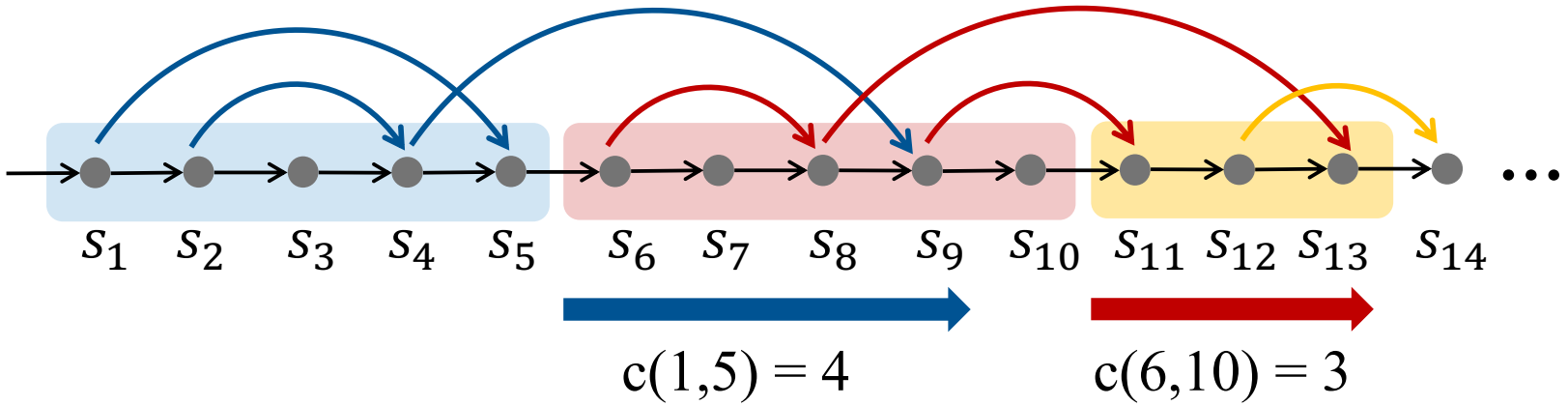
$$r(\tau) = \max\{\, d : \Delta T(d, \tau) \geq \varepsilon \,\}$$

Keep $(s_i, s_j) \in E$ **iff** $d_{ij} \leq r(\tau_{ij})$



Straight line: a simple chain. Raster and spiral: revisits add edges, so the graph gets denser.

DAG partitioning: N segments onto M ranks

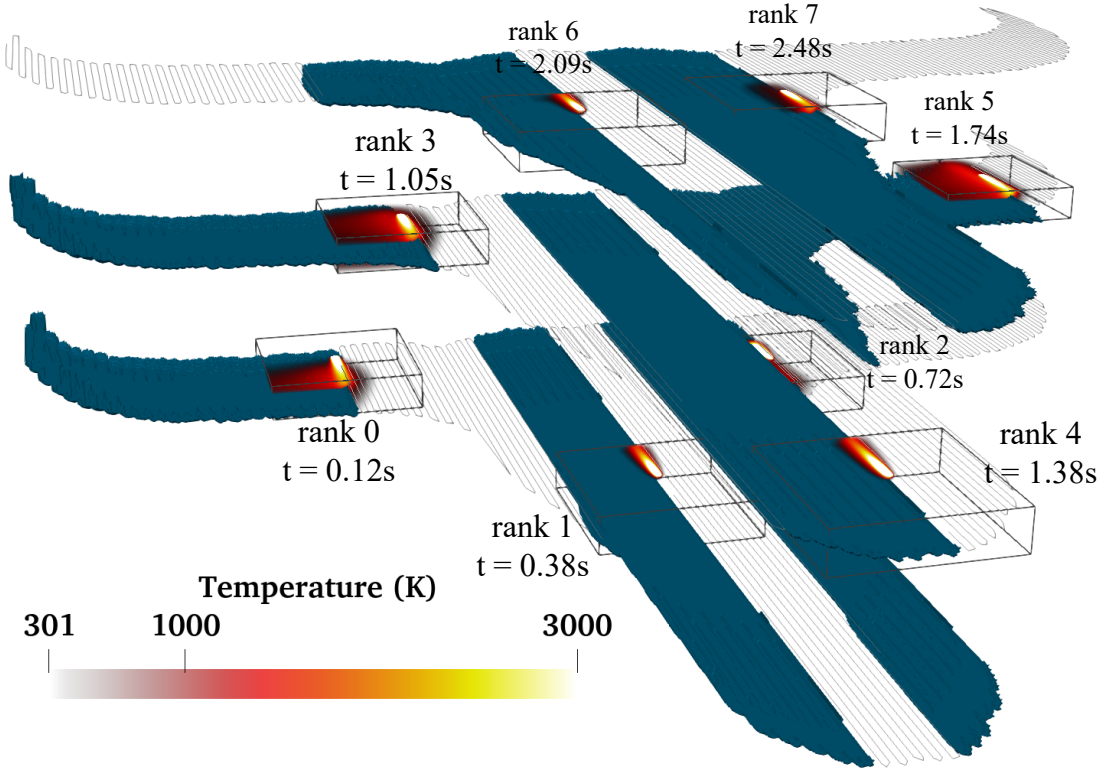


Inside a rank: solved sequentially

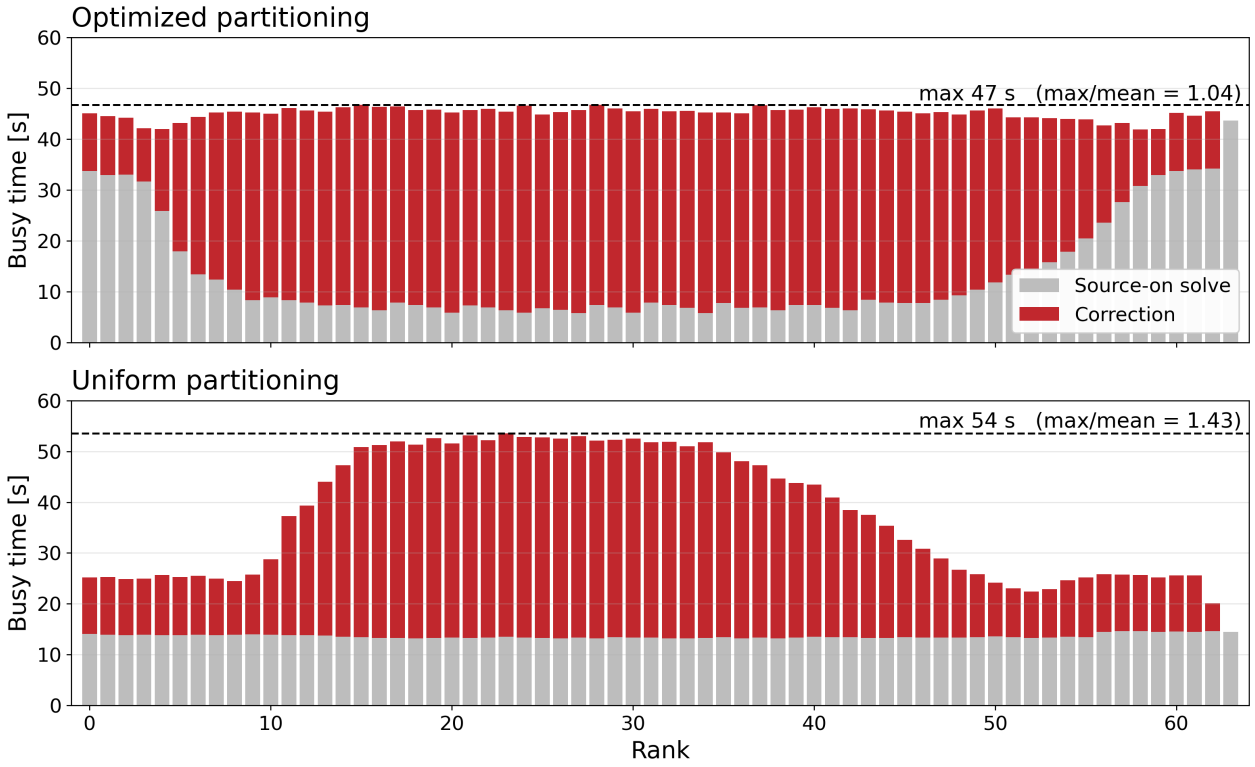
Across a rank boundary: adds correction work, measured by the cut depth c

Objective: $\min_{\text{partition}} \max_{\text{rank}} \left(n\, w_{\text{src}} + c\, w_{\text{corr}} \right)$

Empirical results



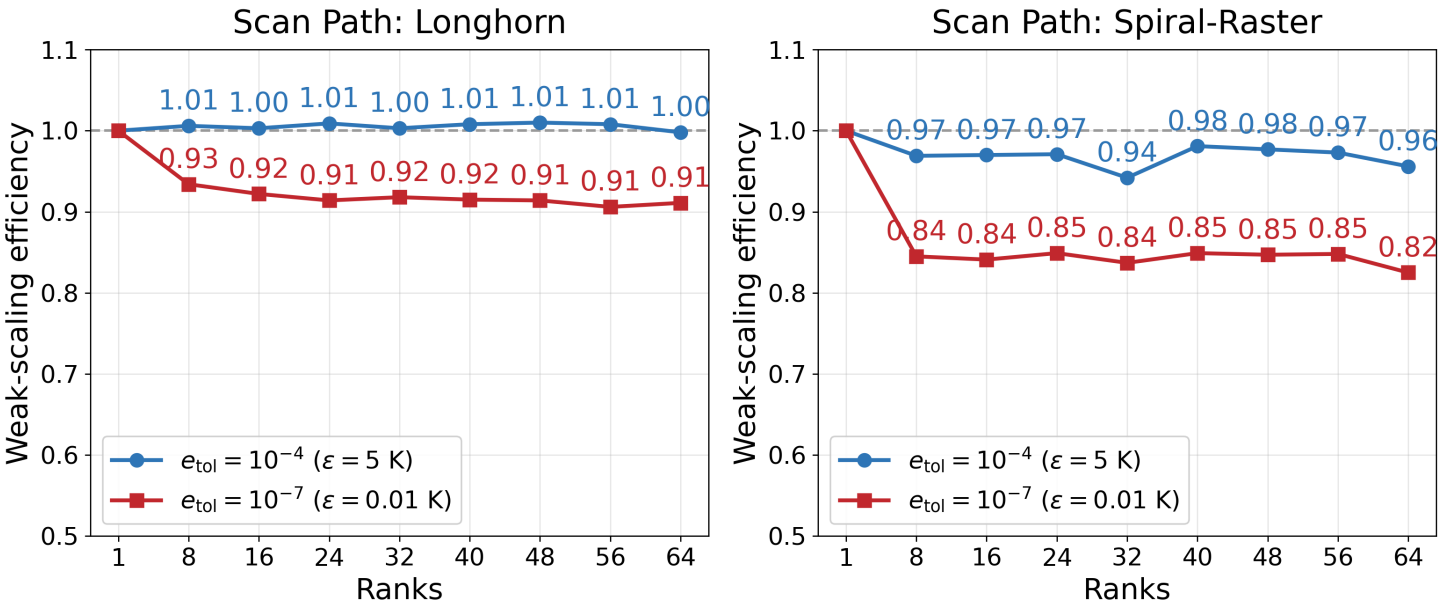
An 8-rank JIFFY simulation of 3-layer Longhorn path build



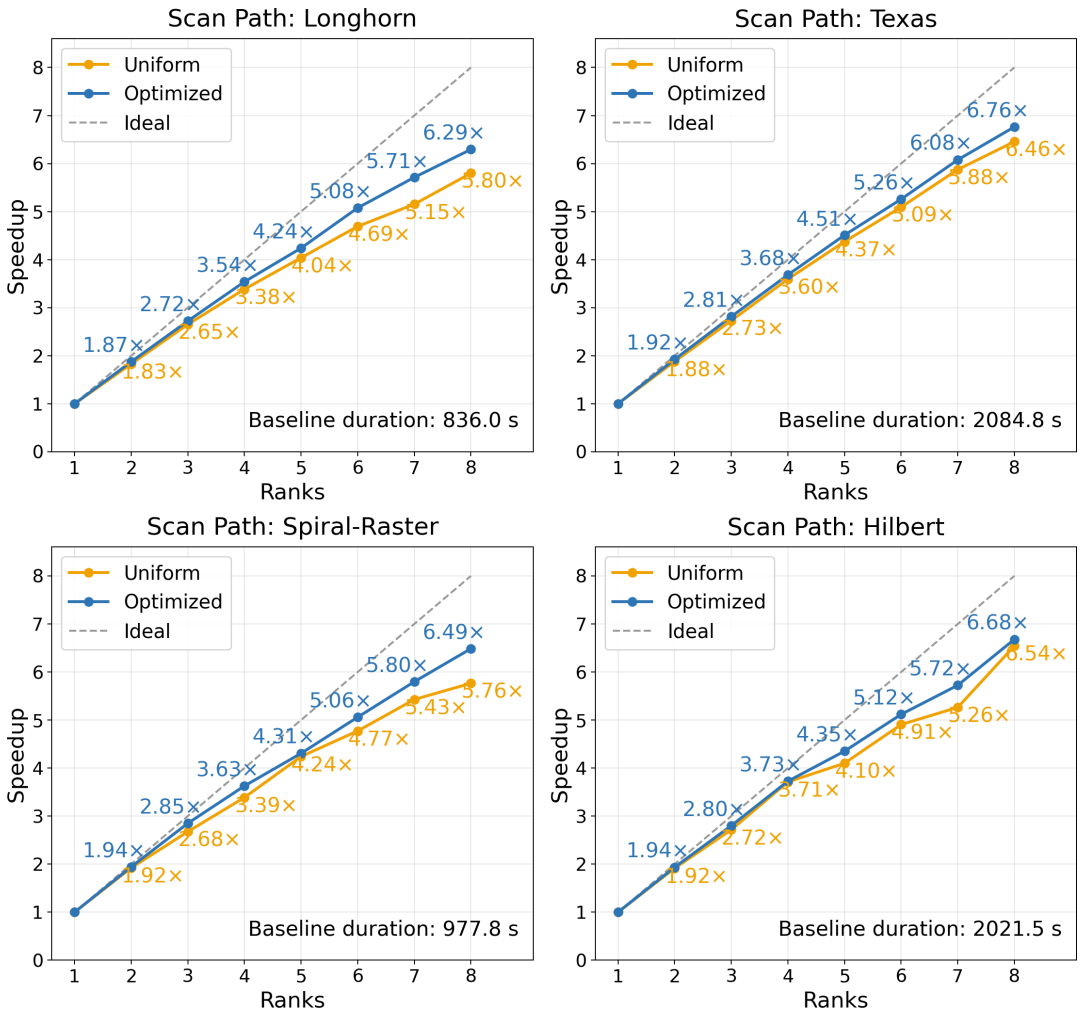
Comparison of per-rank wall time for 1-layer Longhorn path using 64 ranks

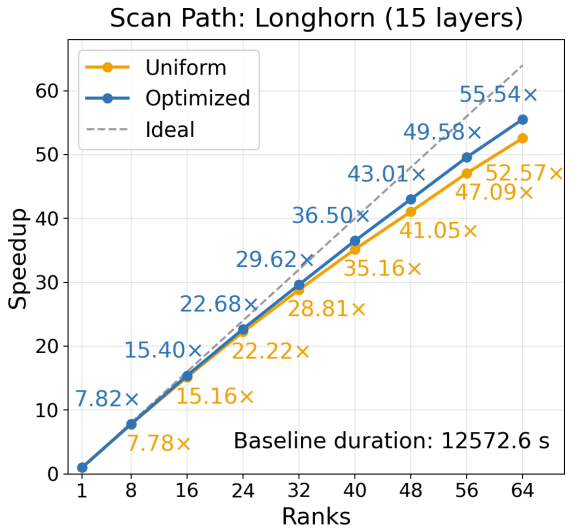
Accuracy and scaling results

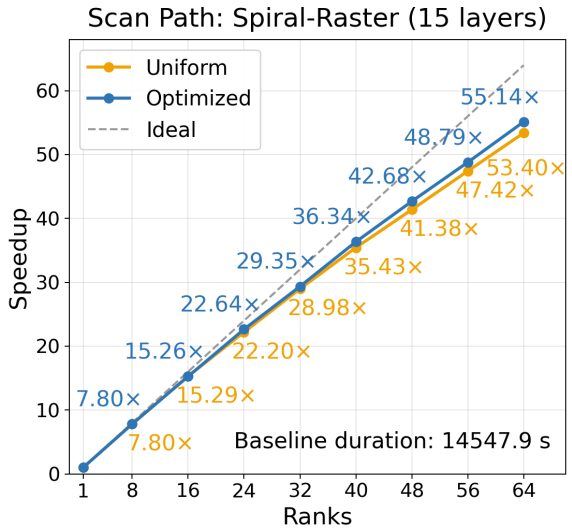
	10^{-4} target, ε = 5 K		10^{-7} target, ε = 0.01 K	
Path	**In-degree**	**Max rel. L^2 error**	**In-degree**	**Max rel. L^2 error**
Straight line	1	9.60×10^{-5}	1	9.81×10^{-8}
Longhorn	22	6.06×10^{-5}	106	3.63×10^{-8}
Spiral–raster	26	6.78×10^{-4}	191	2.35×10^{-8}



Strong scaling







Conclusions

- Fast parallel-in time, moving domain in space solver for additive manufacturing processes
- Graph-based time-parallel partitioning based on heat Greens' function
- Provable accuracy
- Excellent weak/strong scaling
- MPI + GPUs
- **LIMITATIONS**
    - Linear heat transfer / simplified physics
    - Single laser
    - Simplified laser source model
    - Not general purpose: assumes particular heat source profile