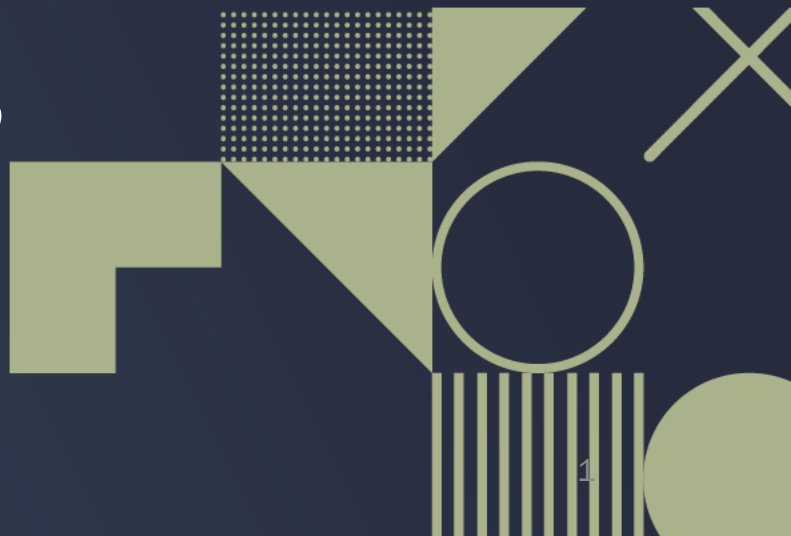
Index Launches: Scalable, Flexible Representation of Parallel Task Groups

Soi, Bauer, Treichler, Papadakis,
Lee, McCormick, Aiken, Slaughter



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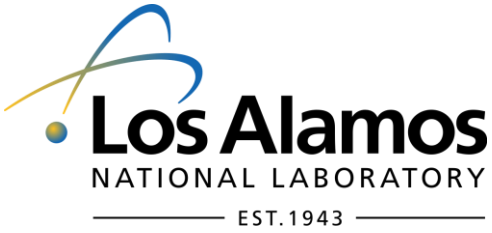
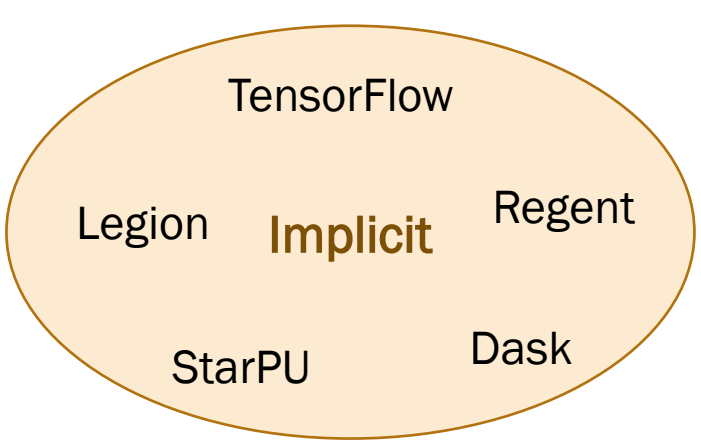
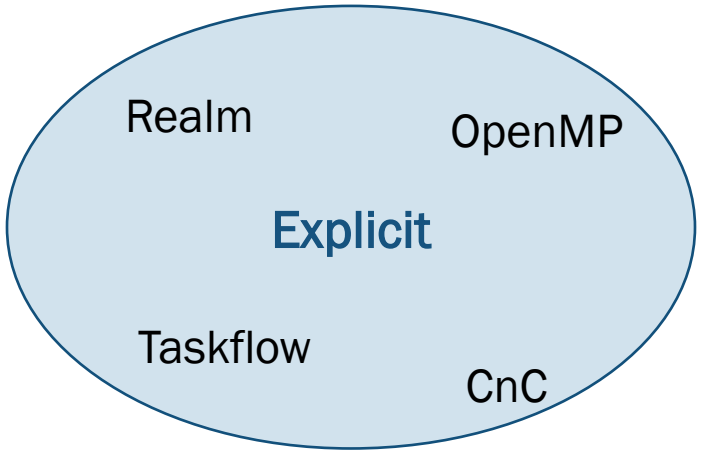
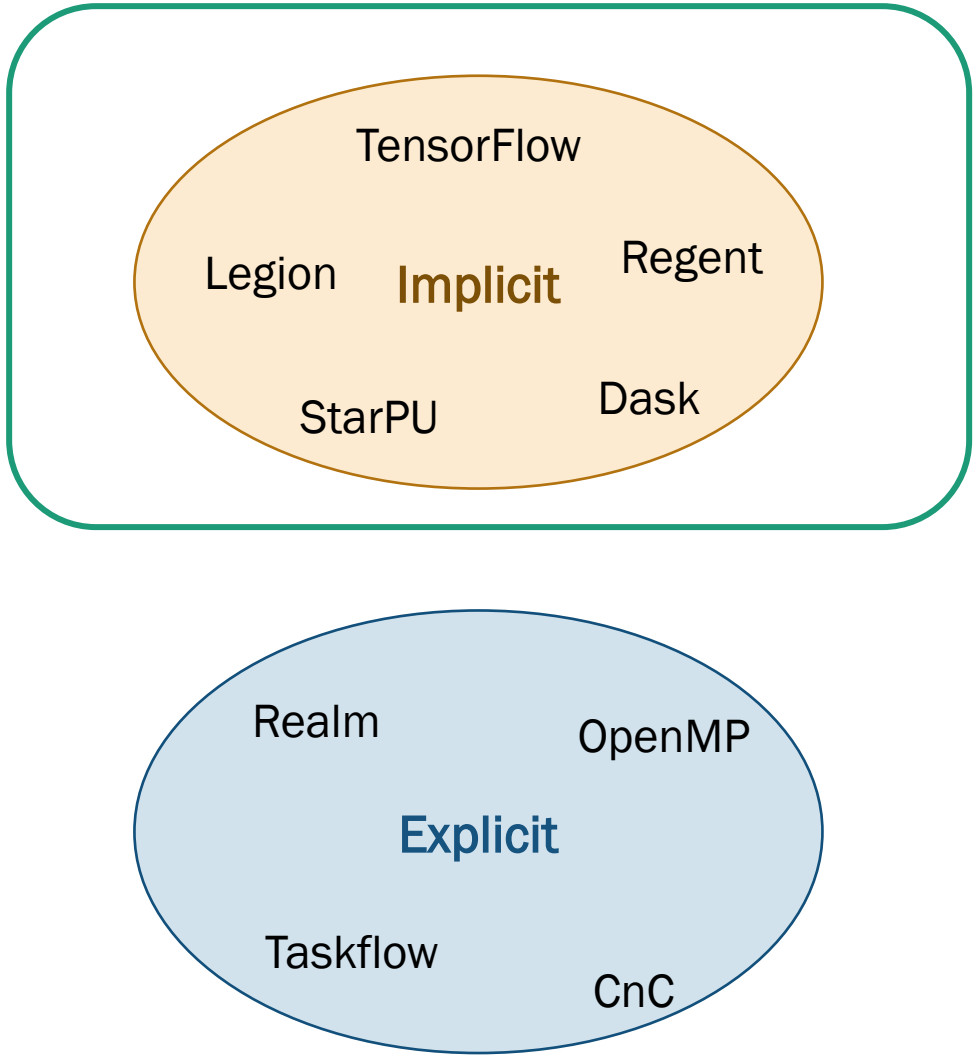


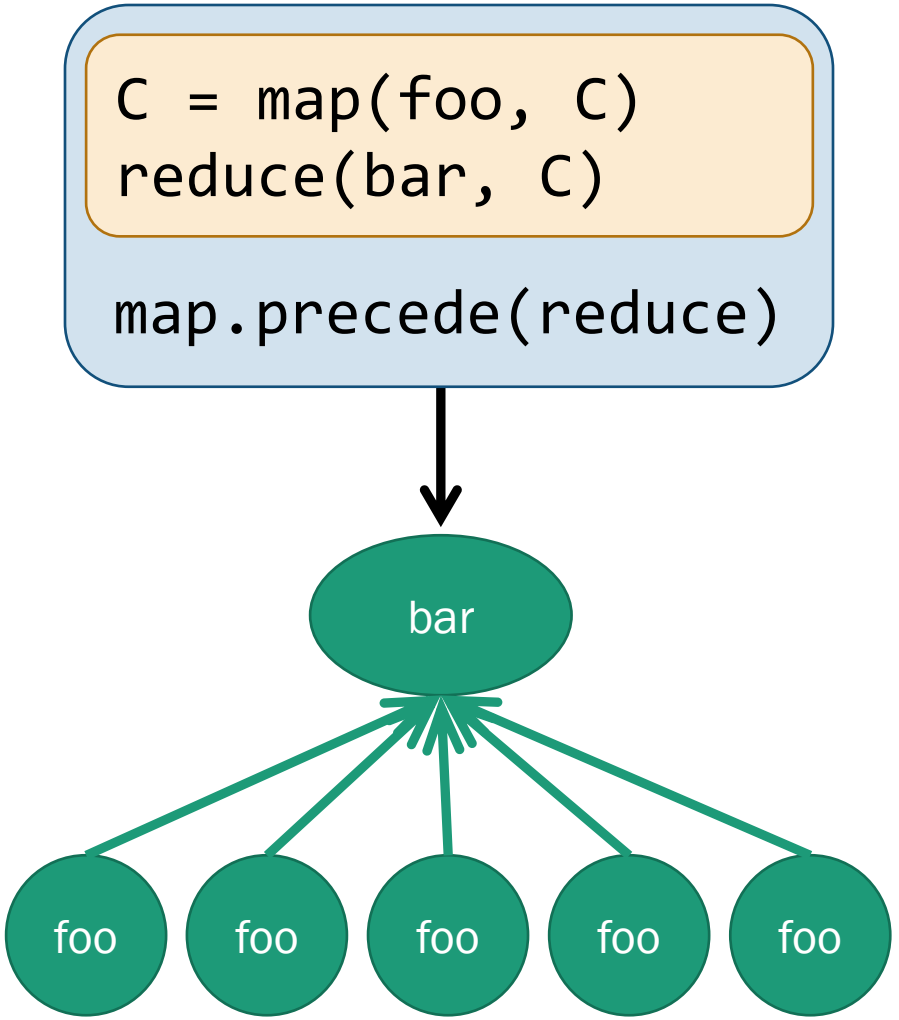
Task-Based Programming Systems





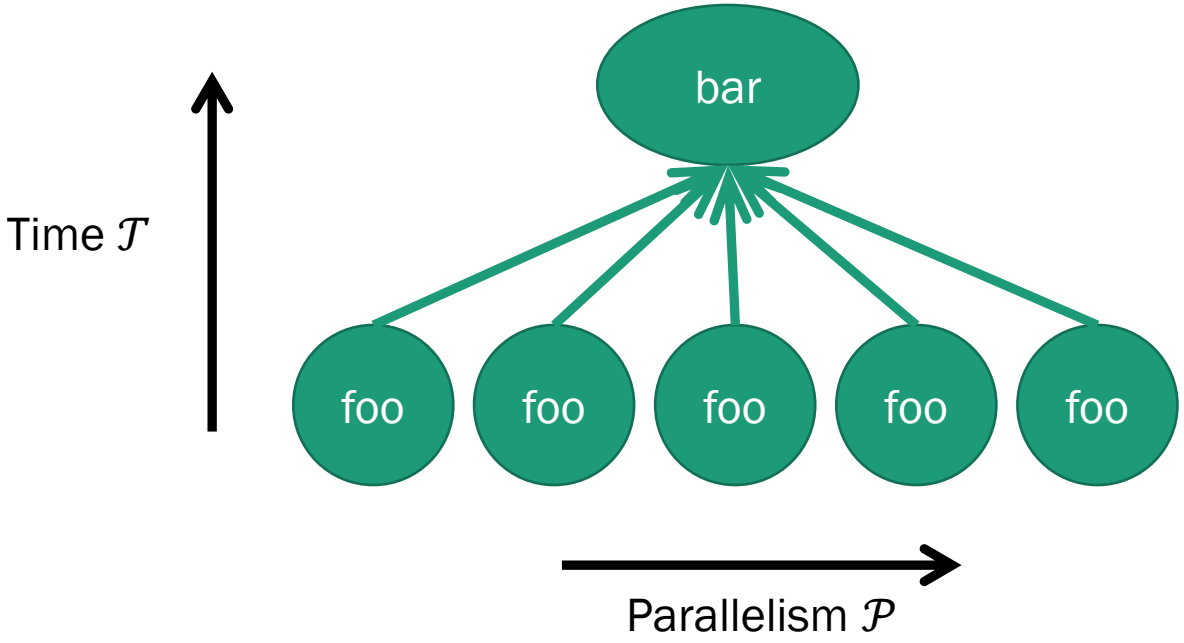
Task-Based Programming Systems





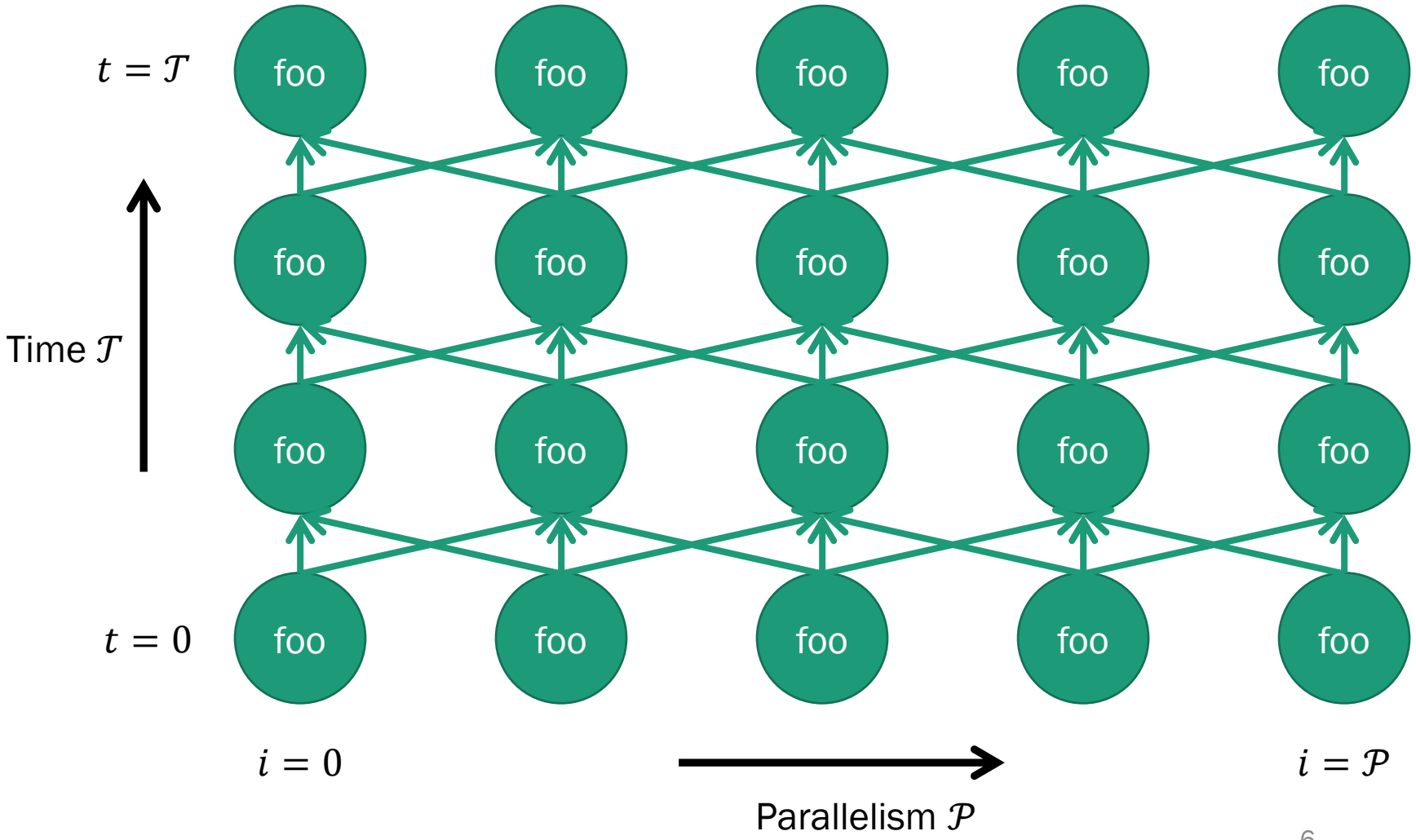
Task Graphs

- Typically, a DAG representing dependences between tasks
- An efficient representation is essential
  - Especially for implicit systems



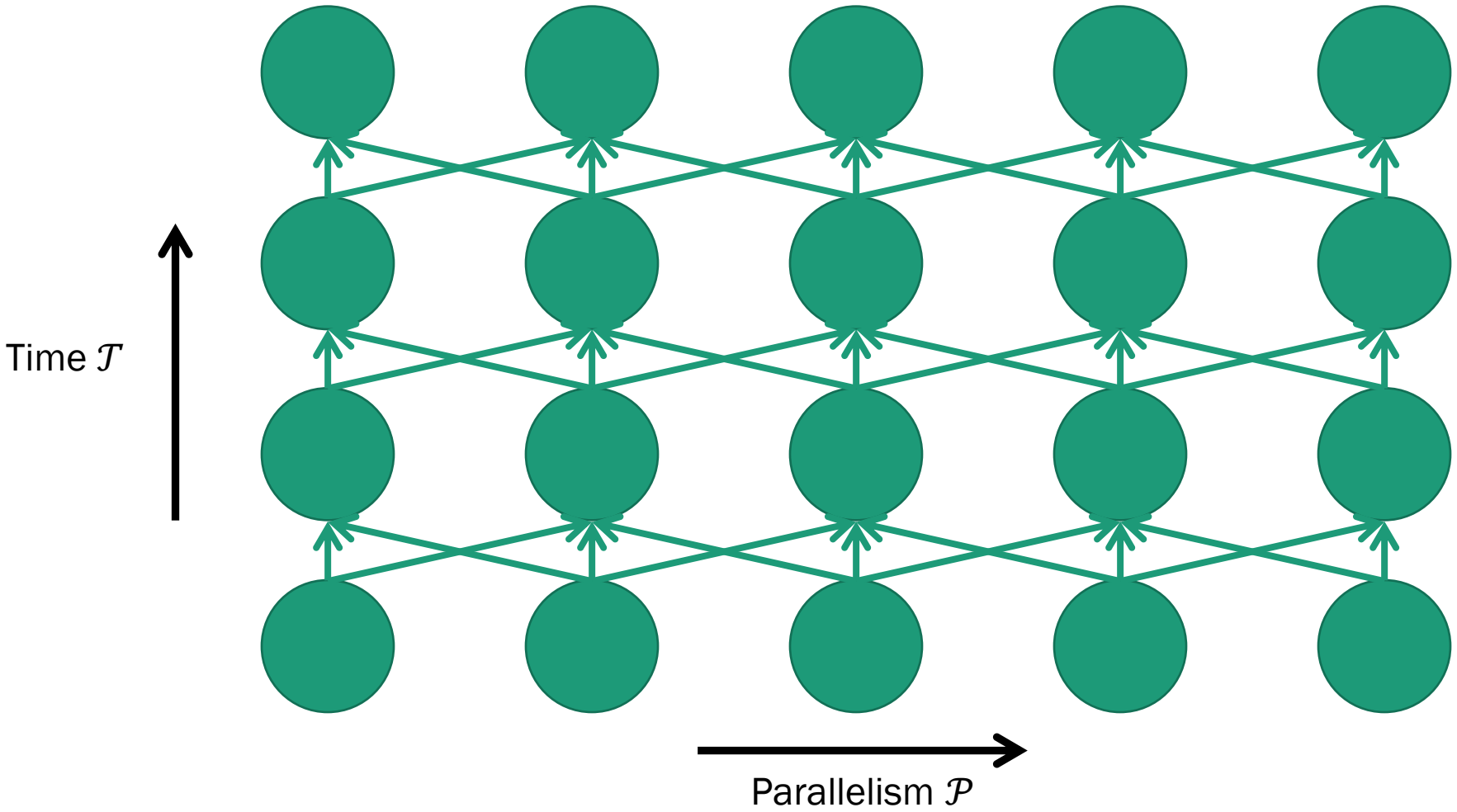
Task Graph Example: Stencil

```
for t = 0, T do
  for i = 0, P do
    foo(C[i-1],
        C[i],
        C[i+1],
        D[i])
  end
  swap(C, D)
end
```



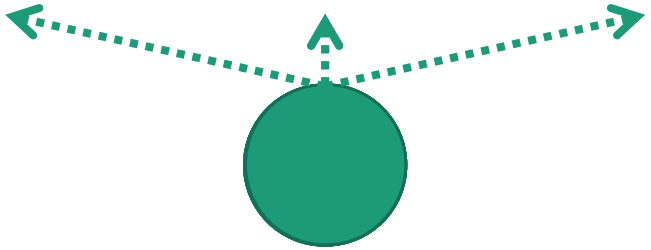
Naïve Representation: $\mathcal{O}(\mathcal{P}\mathcal{T})$

10^6 tasks/sec in large applications

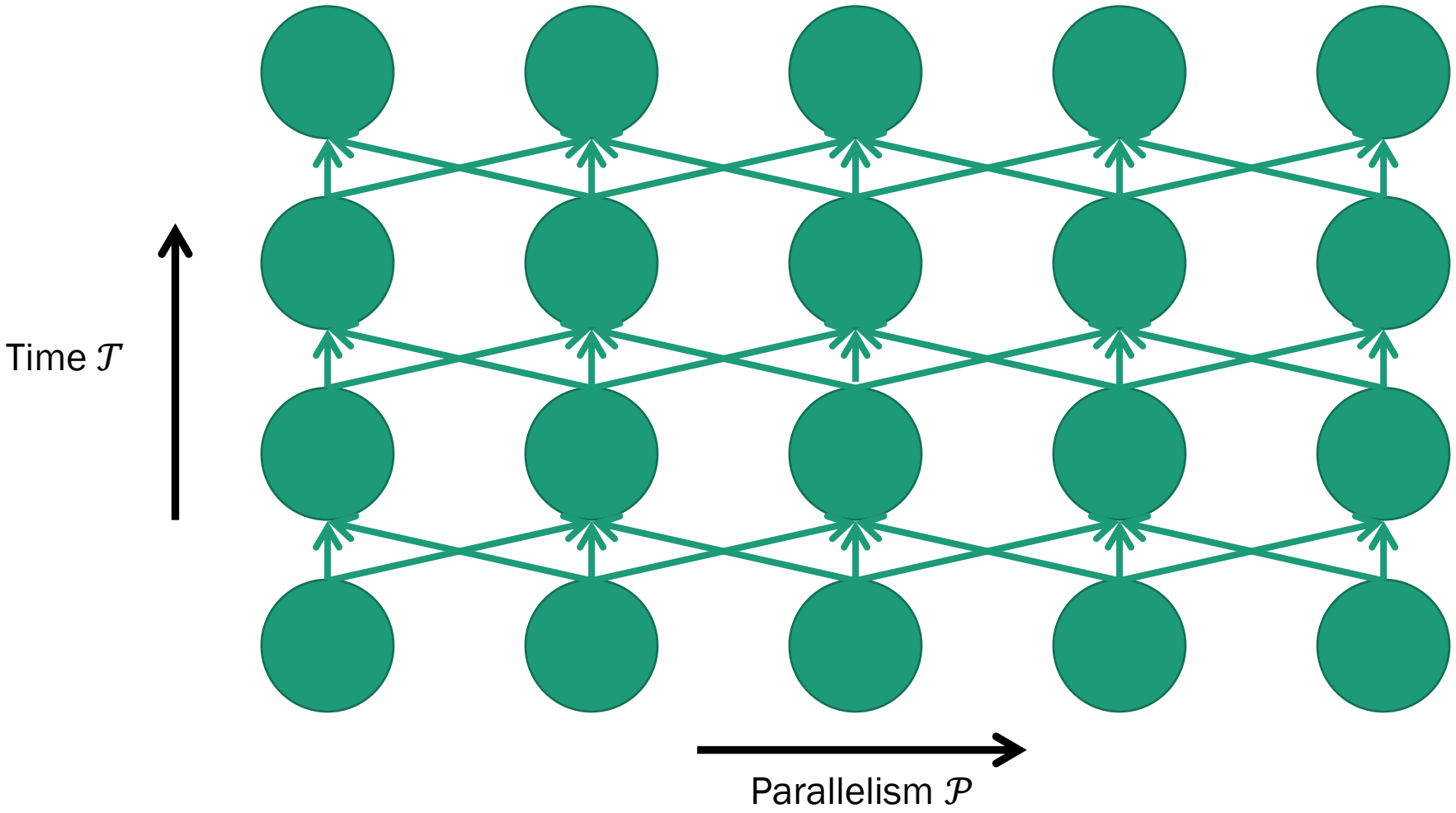


Collapsing Time & Parallelism: $\mathcal{O}(1)$

- PaRSEC PTG captures a static, algebraic task graph
- Maximally dense, but limited expressiveness
  - Cannot express dynamic task generation

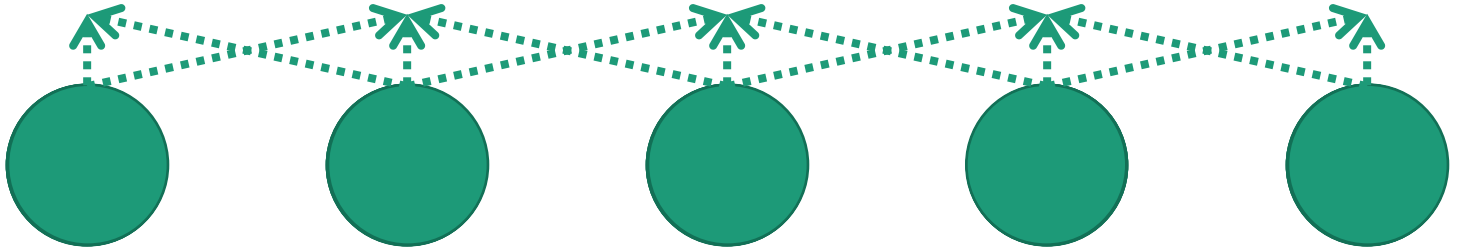


Naïve Representation: $\mathcal{O}(\mathcal{P}\mathcal{T})$

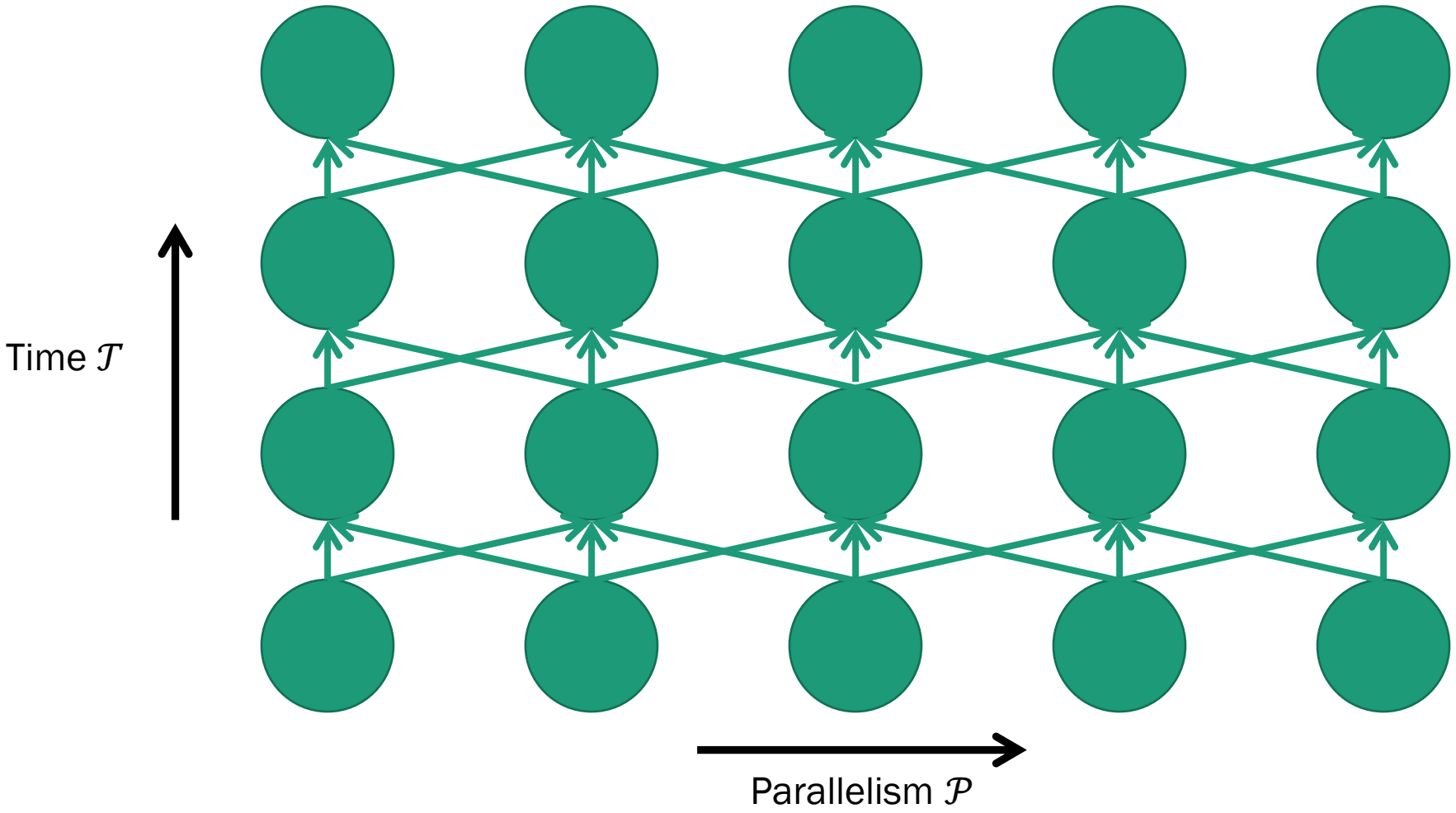


Collapsing Time: $\mathcal{O}(\mathcal{P})$

- TensorFlow represents control-flow in-graph
- Runtime needs to see the entire graph at once to collapse it. Impossible if:
  - the program is submitted incrementally, or
  - its control flow is not understood by the compiler

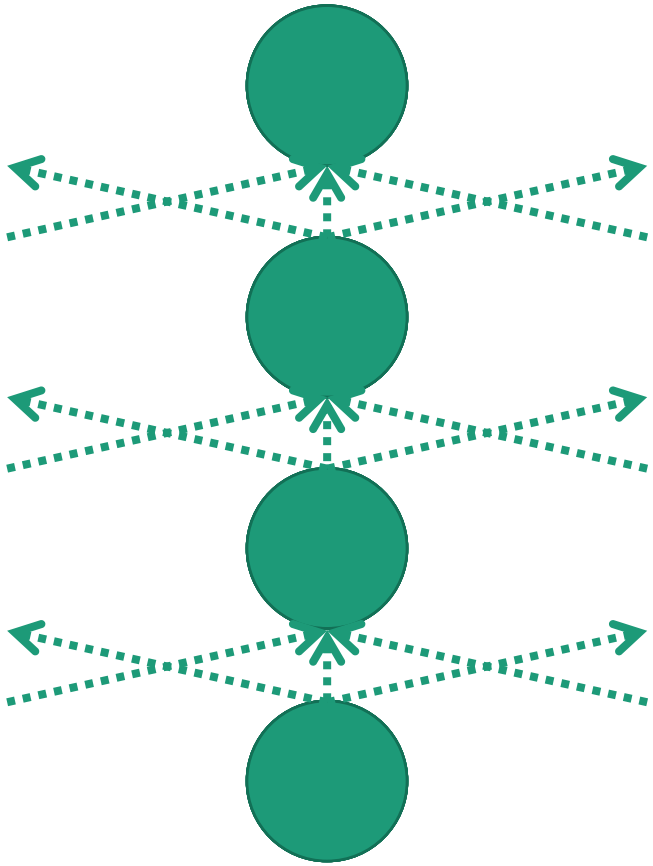


Naïve Representation: $\mathcal{O}(\mathcal{P}\mathcal{T})$



Collapsing Parallelism: $\mathcal{O}(\mathcal{T})$

- Our solution: Index Launches
- Programs benefit from the reduced runtime overhead
- We support arbitrary and dynamic control flow
- Implementation with Legion and Regent



Each node is now an index launch

Data Model

Data Model: Collections

- Any data structure containing homogeneous objects
- Often indexed in N-D
- The primary way to pass large data to tasks

(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)
(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)
(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)
(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)

Data Model: Partitions

- Dividing a collection into sub-collections
  - Tasks that access disjoint data can run in parallel
- Can be *disjoint* or *aliased*
  - Unlike mathematical partitions, which are disjoint by definition
- Exact method is unimportant for this talk

$|P| = 4$

(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)
(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)
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(v_x, v_y)	(v_x, v_y)	(v_x, v_y)	(v_x, v_y)

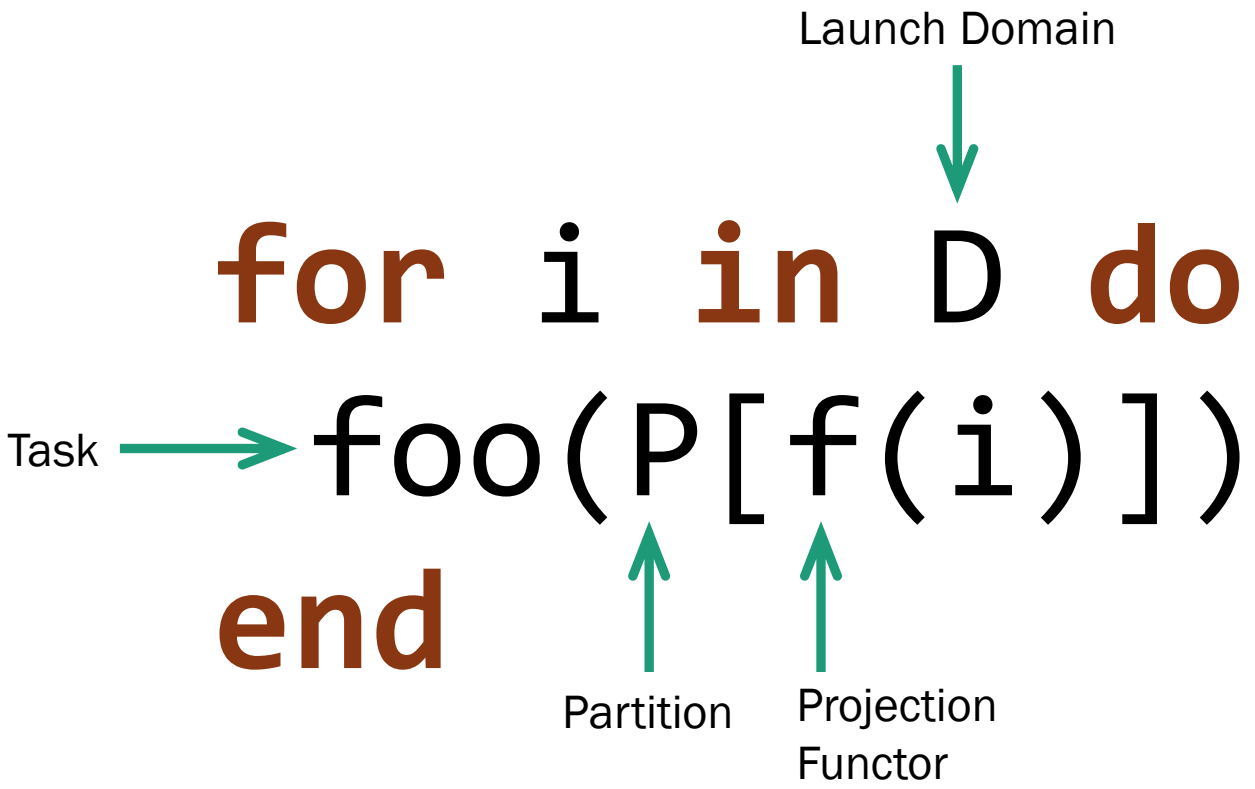
Data Model: Privileges

- Tasks declare privileges on collections they receive as input
- Privileges include read, write, and reduce (+, *, min, …)
- Required by the system for dependence analysis

```
task foo(C, D) reads(C) writes(D)
do
   -- computation
end
```

Index Launches

Elements of an Index Launch



When is an Index Launch Safe?

- When all tasks in the launch are safe to run in parallel
- Below: assume P is disjoint and *foo* has write privileges

```
for i in D do
  foo(P[0])
end
```

Unsafe, because two different tasks may write to P[0]

```
for i in D do
  foo(P[i])
end
```

Safe

Compiler Guarantees Safety

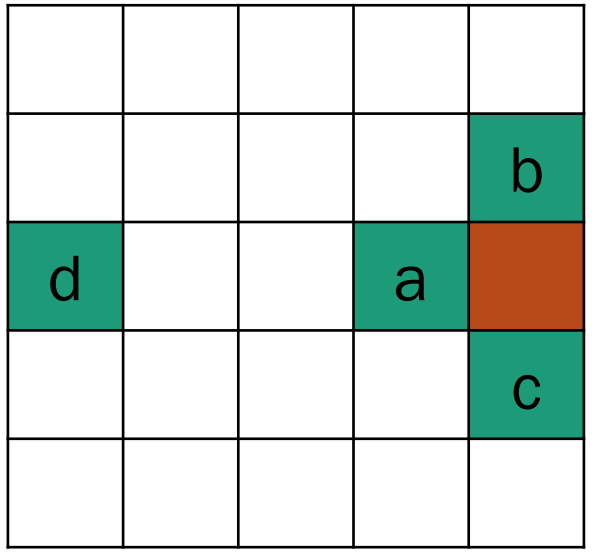
- Safety depends on:
  - Disjointess of the partition
  - Privileges of the task
  - Projection functor
- The programming model can facilitate the static analysis of privileges and disjointness:
  - Task with only read privileges on any partition is safe to index launch
  - Task with write privileges on an aliased partition is unsafe to index launch

Most common: disjoint partition with write privileges

The Problem of Projection Functors

- Can be arbitrary pure functions
- Hard to analyse statically

$$f_a(x, y) = (x - 1, y) \pmod N$$
$$f_b(x, y) = (x, y + 1) \pmod N$$
$$f_c(x, y) = (x, y - 1) \pmod N$$
$$f_d(x, y) = (x + 1, y) \pmod N$$



Periodic Launch Domain

Static and Dynamic Analysis for Projection Functors

- If the task has write privileges, then the projection functor must not assign two different calls the same data
  - Must be injective over the launch domain
- Static analysis for easy, common cases (e.g. identity)
- Dynamic analysis otherwise
  - Iterate over the launch domain and check for duplicate values
  - Precondition: the partition must be disjoint

Dynamic Analysis Algorithm

1. Create a bitmask as large as $|P|$
2. Iterate over D and set the bitmask at each value of f
3. Exit if a duplicate is found

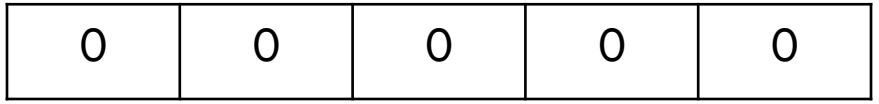
Our analysis works at the granularity of sub-collections

$$D = [0, 4]$$

$$|P| = 5$$

$$f(i) = i \pmod 3$$

Bitmask



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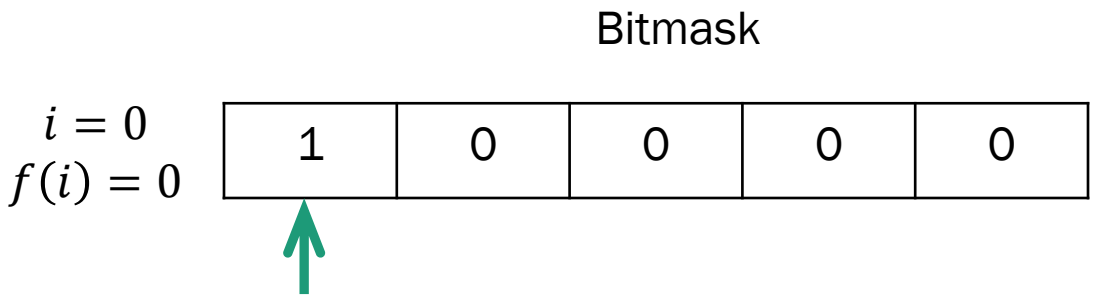

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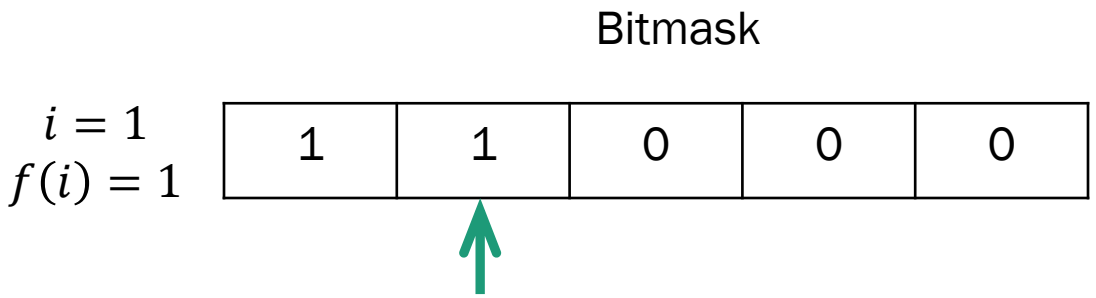

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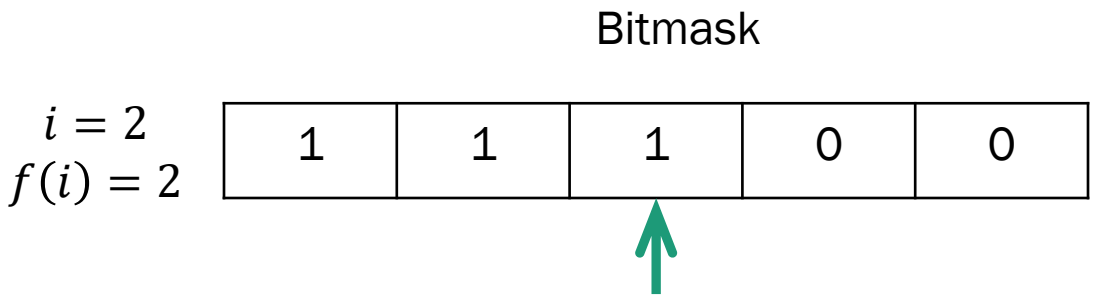

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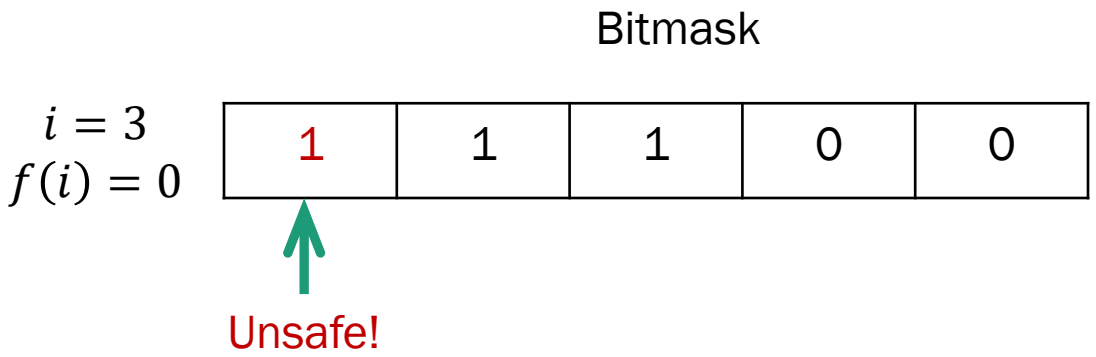
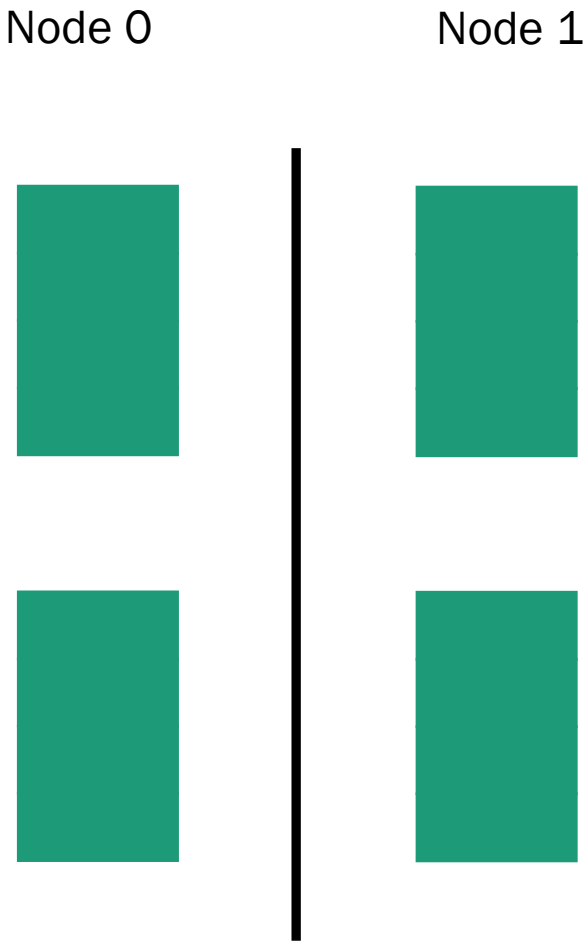


Runtime Implementation

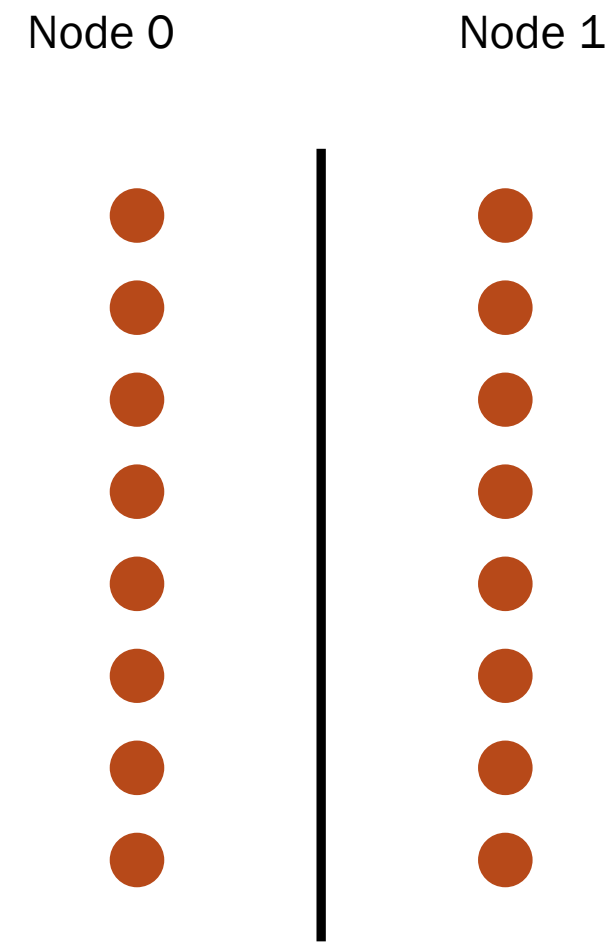
Legion Runtime

- Needs to efficiently execute index launches
- Two modes: this talk uses the newer, distributed mode
  - See Bauer PPoPP ’21
- Has an internal pipeline to process tasks

Pipeline Stage I: Task Issuance

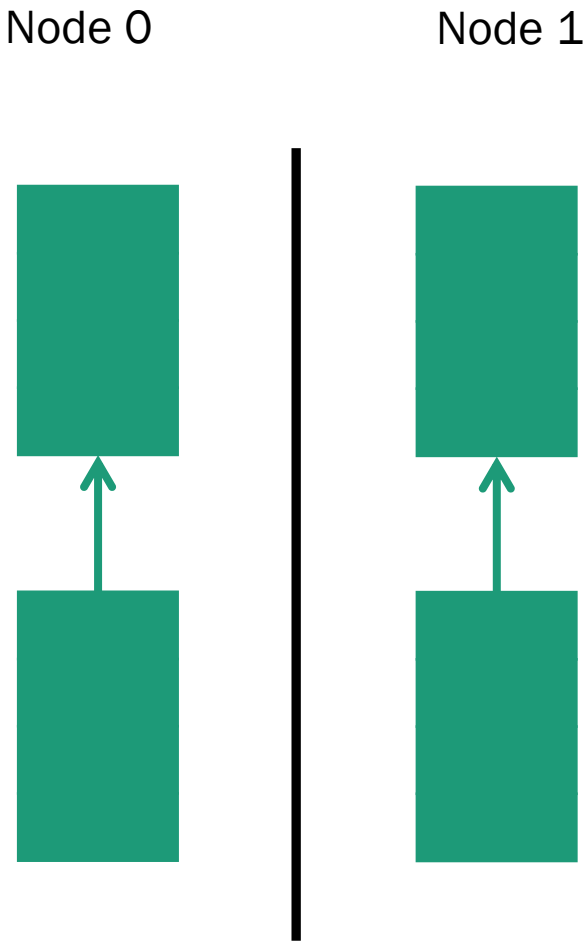


with Index Launches

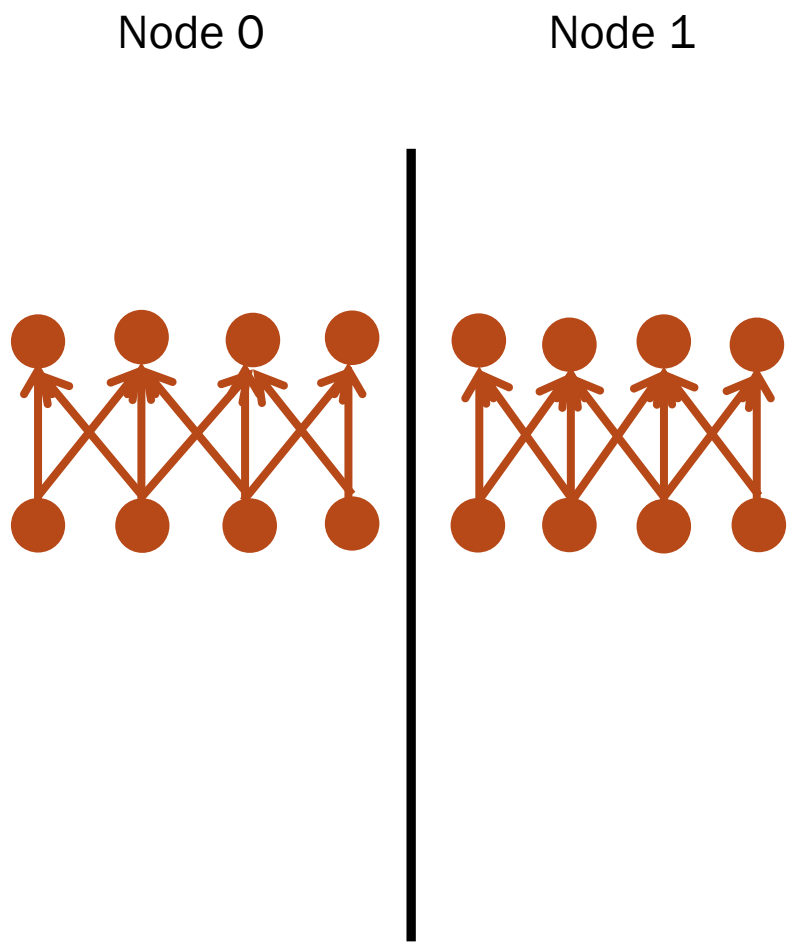


without Index Launches

Pipeline Stage II: Logical Analysis



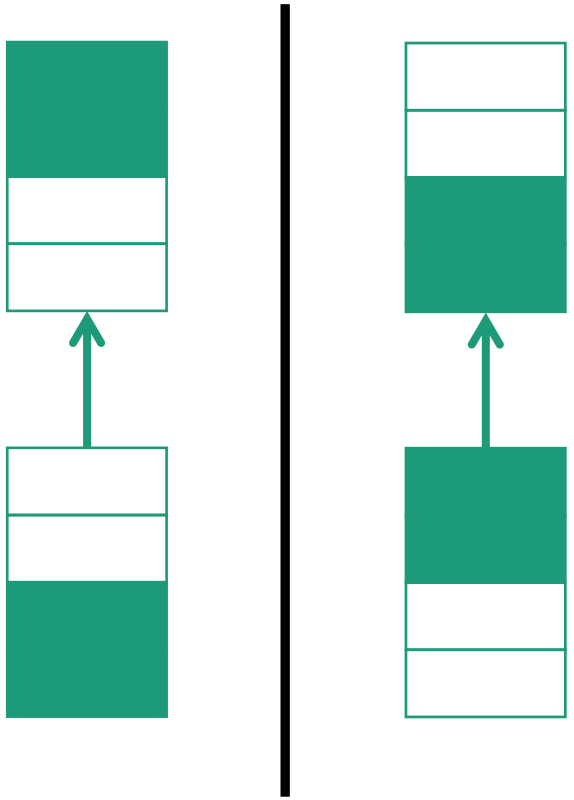
with Index Launches



without Index Launches

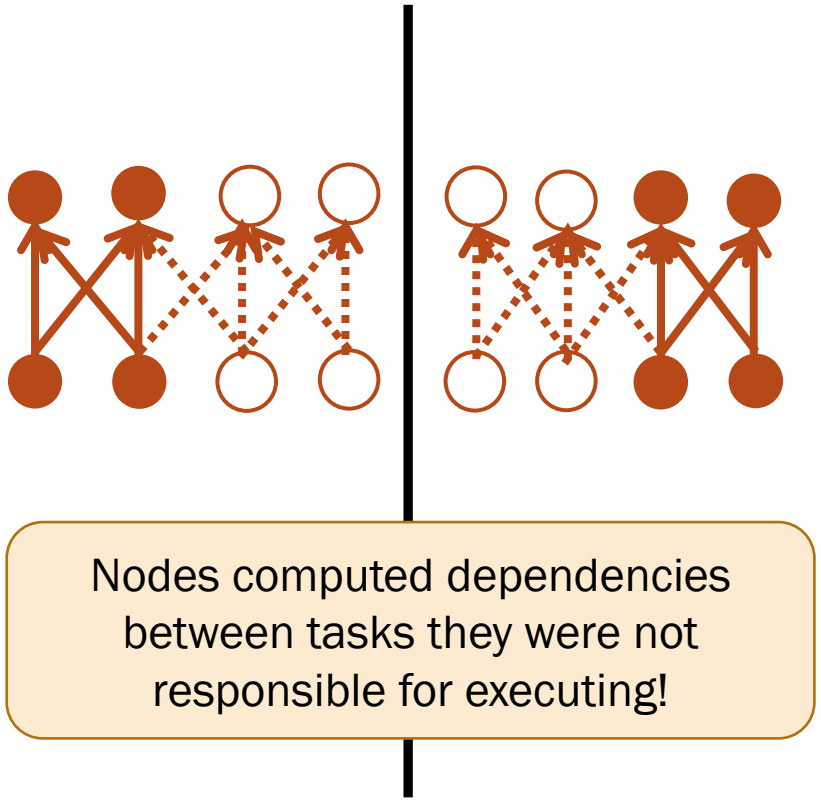
Pipeline Stage III: Distribution

Node 0 Node 1



with Index Launches

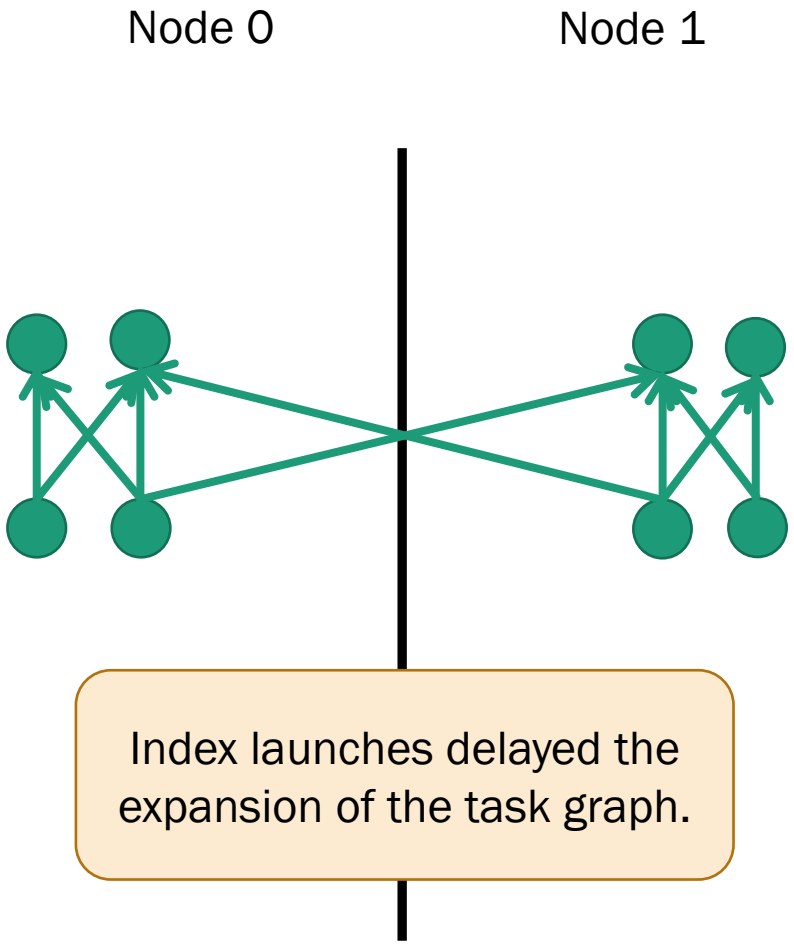
Node 0 Node 1



Nodes computed dependencies between tasks they were not responsible for executing!

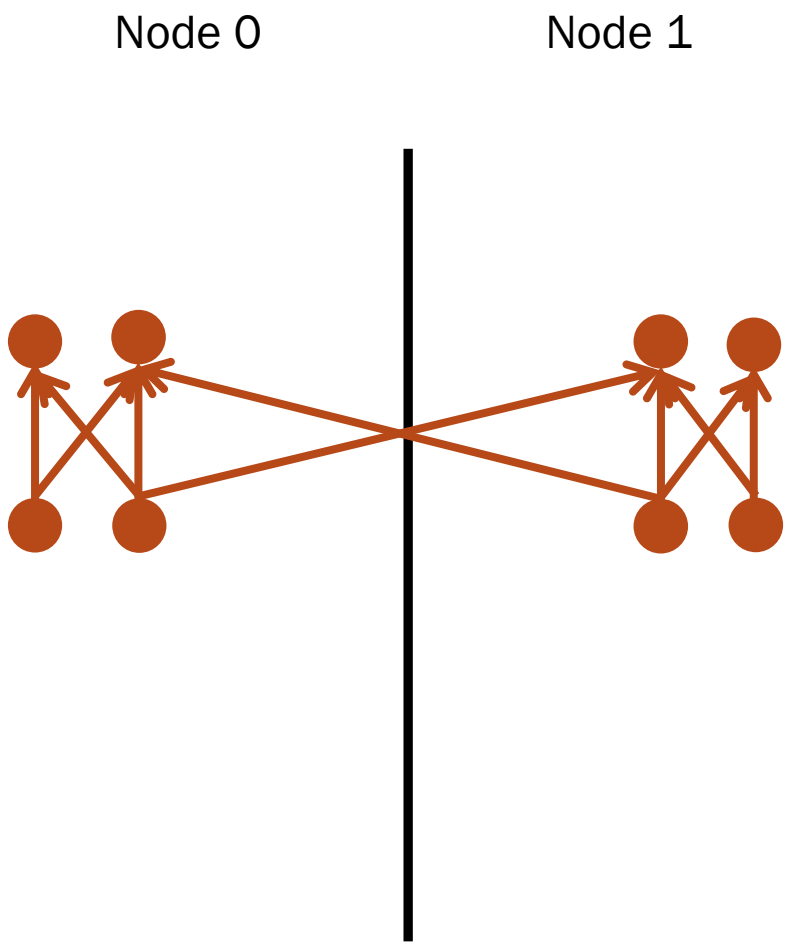
without Index Launches

Pipeline Stage IV: Physical Analysis



Index launches delayed the expansion of the task graph.

with Index Launches



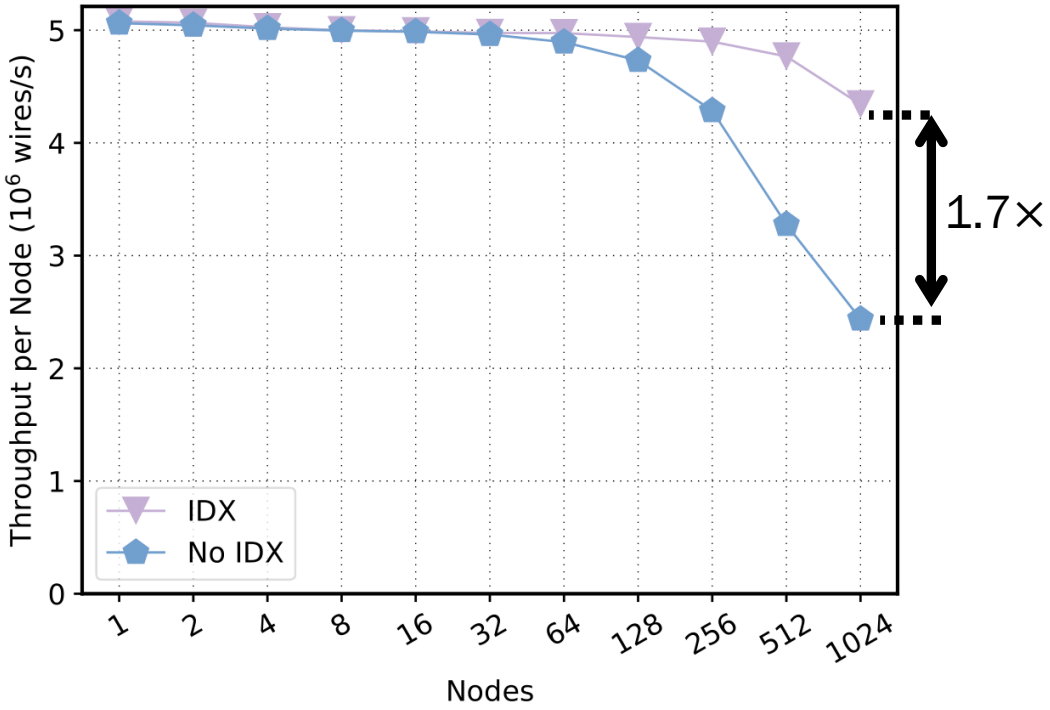
without Index Launches

Performance Evaluation

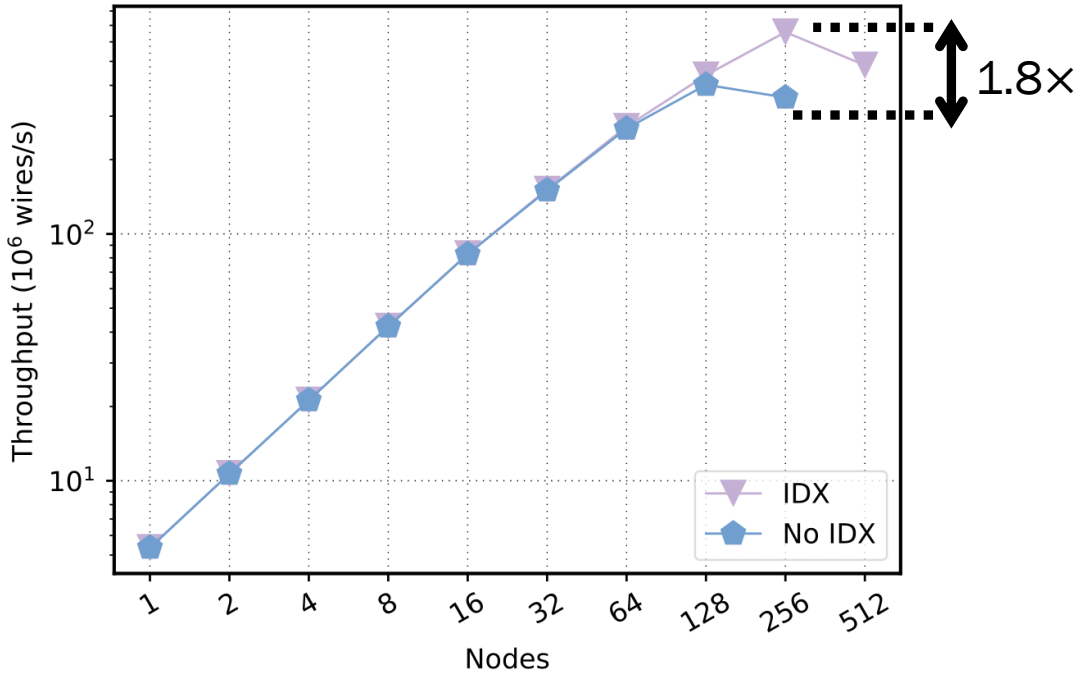
Experimental Setup: Piz Daint

Model	Cray XC50
CPU	Intel Xeon E5-2690 v3
GPU	NVIDIA Tesla P100
Interconnect	Cray Aries
Nodes	1024

Performance Evaluation: Circuit

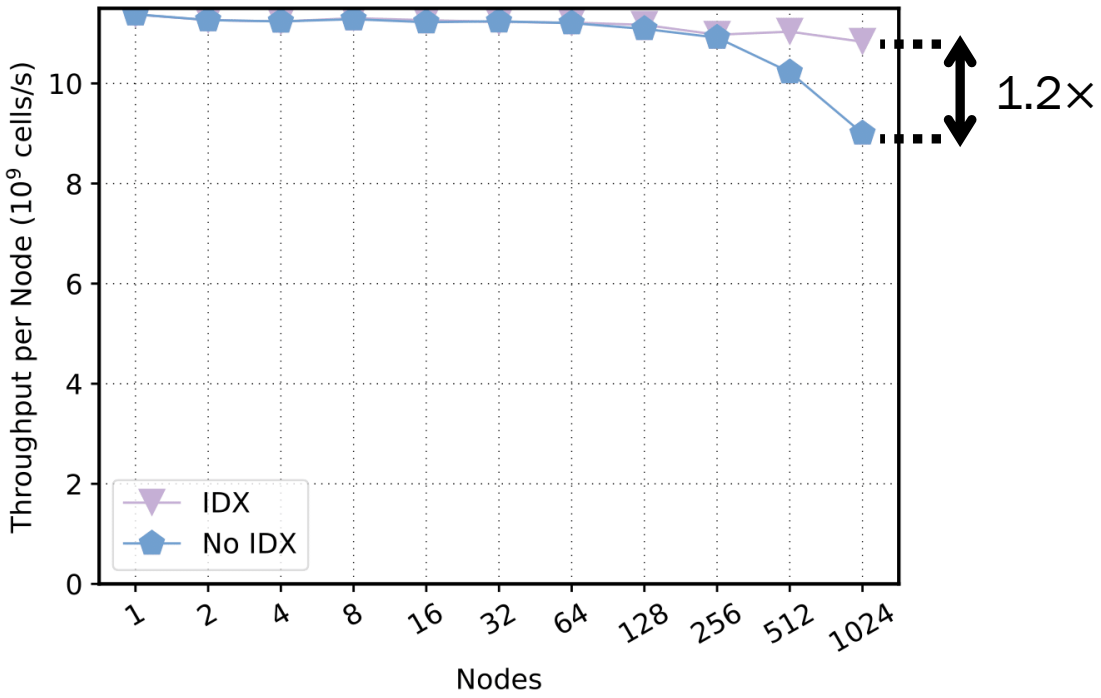


Weak Scaling

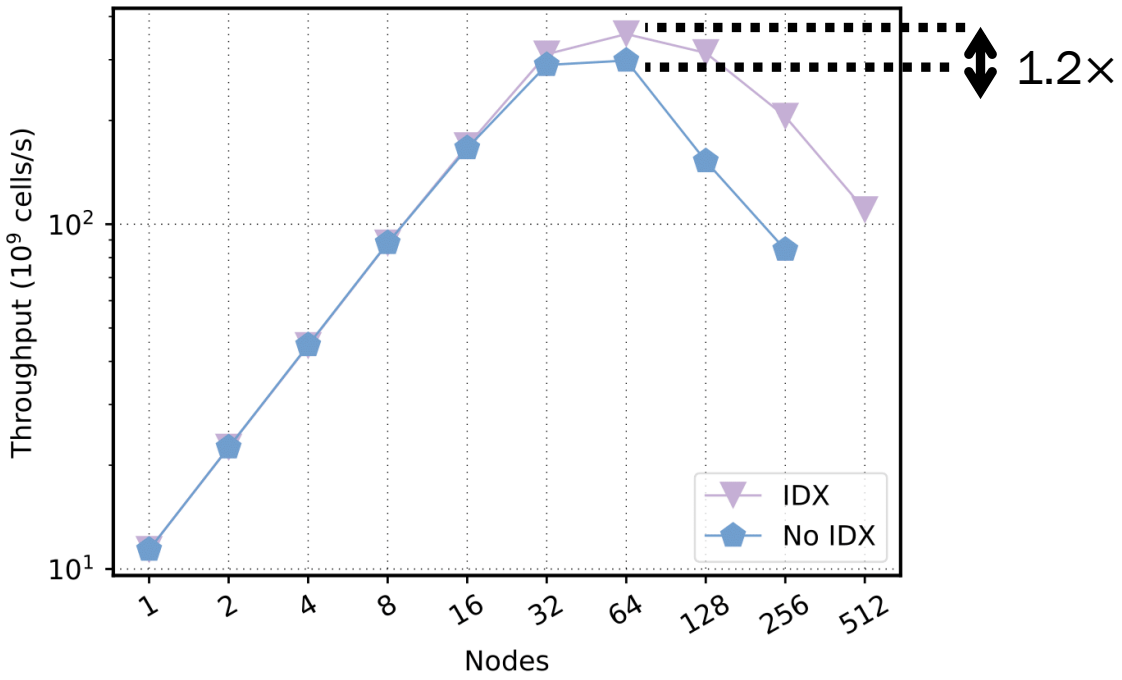


Strong Scaling

Performance Evaluation: Stencil

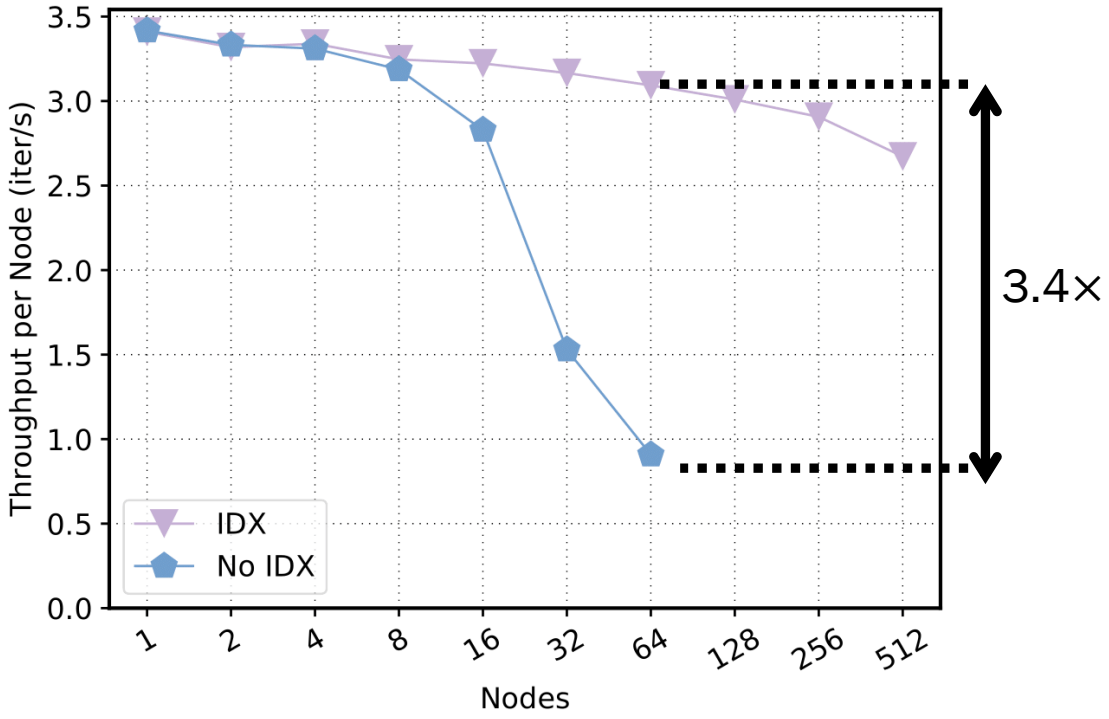


Weak Scaling

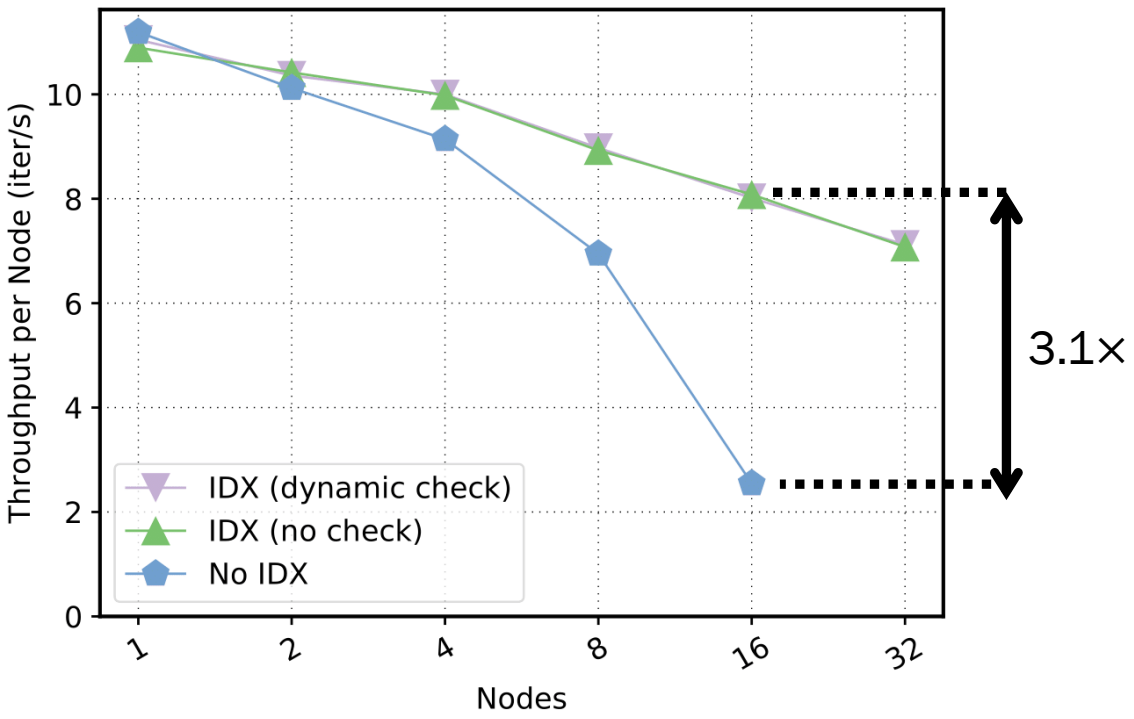


Strong Scaling

Performance Evaluation: Soleil-X



Weak Scaling, Fluid only



Weak Scaling, Fluid + Particle + DOM

Contributions

- Classification of task-based systems
  - Based on how they collapse the task graph
- Index launches as a general technique
  - Main elements: task, partition, projection functor
- Implementation in Legion and Regent
  - Index launches delay the expansion of the task graph at runtime
- Performance evaluation
  - Upto 3× speed-ups in scientific applications

More in the Paper!

- More sophisticated dynamic analysis
- Legion's centralized mode of dependence analysis
- More experiments
- …

Related Work

- Legion (Bauer SC ’12)
  Regent (Slaughter SC ’15)
  DCR (Bauer PPoPP ’21)
- TensorFlow (Yu EuroSys ’18)
- Dask (Rocklin SciPy ’15)
- PaRSEC (Bosilca ’13)
- Taskflow (Huang TPDS ’21)

Acknowledgments

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