Fine-Grained Locks for Multithreaded Grid Operations

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Motivation

Desktop Environments

Generic Binary

It’s very hard to bundle MPI in a generic binary for usage distribution. (e.g., multi-platform GUI)

Multi-Tasking

Program is shared with other unknown tasks that may need higher priority.

High Performance Computing

Surface-to-Volume Ratio

High dimension or high polynomial degree FE problems suffer from a high surface-to-volume ratio. This translates on higher communication overhead.

Node Level Load Balancing

Sharing memory between processes allows the use of fair work stealing algorithms

Assembly of Finite Elements

Volume Integrals

```
def residual(test, trial, coeff):
    ltest = test.localView()
    ltrial = trial.localView()
    residual = [0., ..., 0.]
    for entity in grid_view:
        bind(entity, ltest, ltrial)
        lcoeff = localVector(coeff, ltrial)
        lresidual = localResidual(ltest, ltrial, lcoeff)
        accumulateVector(residual, ltest, lresidual)
    return residual
```

```
def localVector(vector, lspace):
    lvector = [0., ..., 0.]
    for dof in range(lspace.size):
        lvector[dof] = vector[lspace.index(dof)]
    return lvector
```

$$\int_T \alpha_V(u_h, v_h) - \lambda_V(v_h)$$

```
def accumulateVector(vector, lspace, lvector):
    for dof in range(lspace.size):
        vector[lspace.index(dof)] += lvector[dof]
```

Assembly of Finite Elements

Data Storage

Data is

- **...*physically organized* arbitrarily in memory**
- **...*temporally accessed* differently depending on the numerics**
- **...*semantically attached* to the topology of the grid**

Assembly of Finite Elements

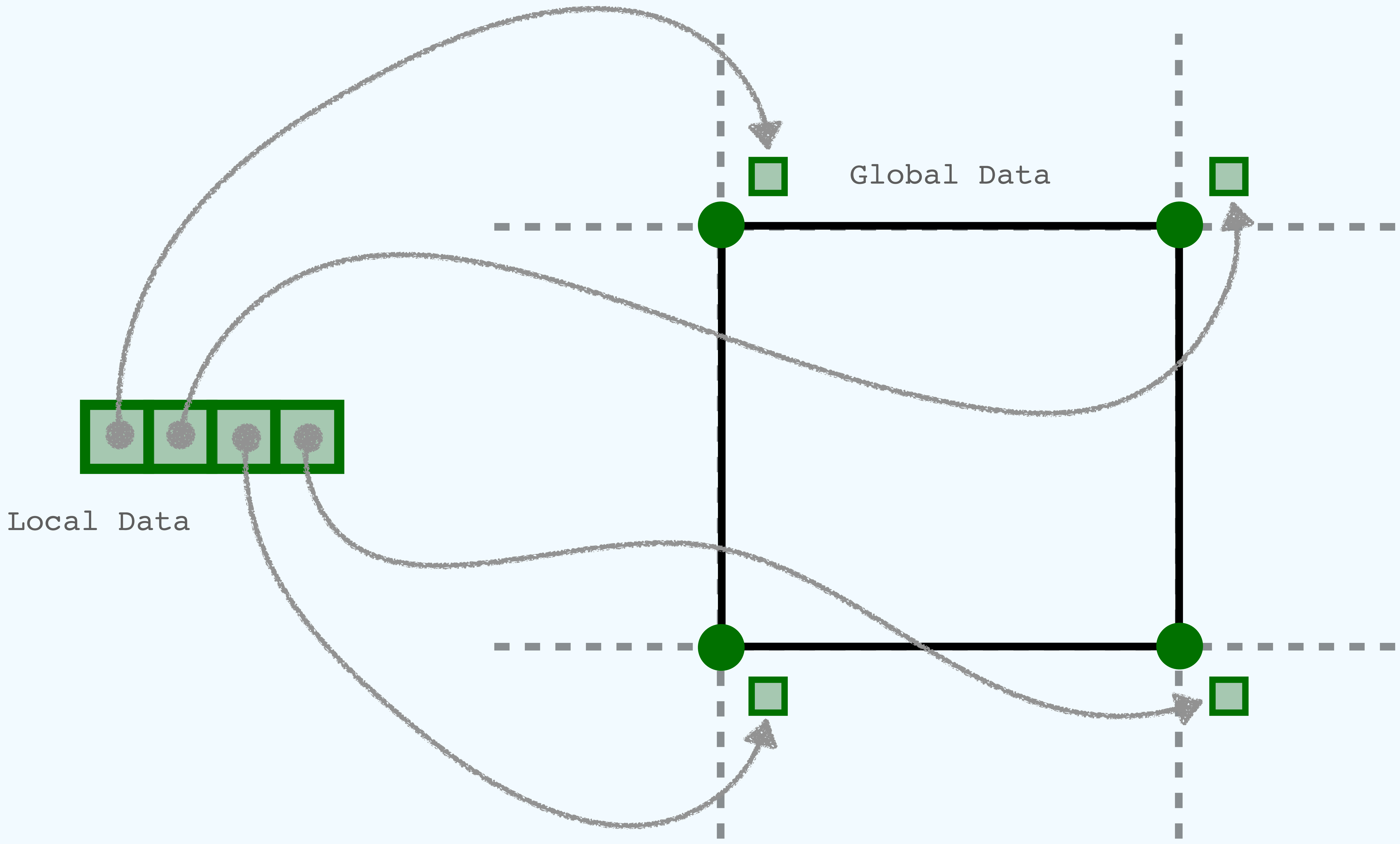
Data Storage

Data is

- …*physically organized* arbitrarily in memory
- …*temporally accessed* differently depending on the numerics
- …*semantically attached* to the topology of the grid

Assembly of Finite Elements

Scatter Data: Local to Global



Assembly of Finite Elements

Grid Partition & Work Scheduling

Mask Shared Region

Fine-Grained Locks

Grid Partition & Scheduling

Where to parallelize?

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def residual(test, trial, coeff):
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Grid Partition & Scheduling

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    return residual
```

Grid Partition & Scheduling

Grid Partition

```
def partition(grid_view, n):
    begin_it = grid_view.begin()
    chunk = grid_view.size(0) / n
    remainder = grid_view.size(0) % n
    ranges = []
    for i in range(n-1):
        next_end = begin_it + (chunk + (remainder ? 1 : 0))
        ranges.append([begin_it, next_end])
        begin_it = next_end
        if reminder:
          reminder = reminder - 1
    ranges.append([begin_it, grid_view.end()])
    return ranges
```

Naive Partition

- \+ Easy: Split iterators in equal chunks
- \+ Generic to any grid
- \+ Enables same cache use as original grid
- \- Unknown size of shared region
- \- Maybe unbalanced

Load Balanced Naive Partition

- \+ Add many (naive) partitions to TBB
- \+ Generic to any grid
- \+ Enables same cache use as original grid
- \+ Automatically balanced
- \- Shared region is bigger than Naive Partition

Critical Section

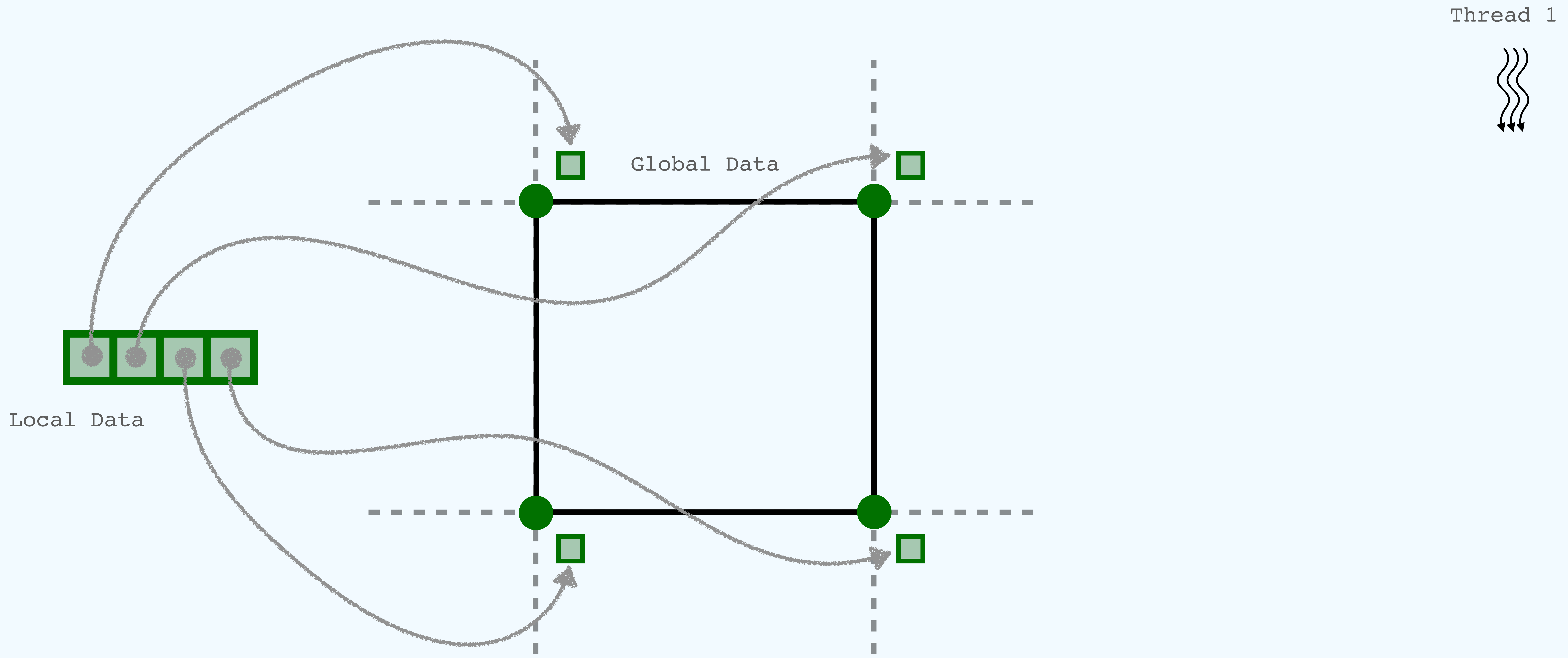
Two or more threads may race to access the same global data

```
def residual(test, trial, coeff):
    ltest = test.localView()
    ltrial = trial.localView()
    residual = [0., ..., 0.]
    for entity in grid_view: # multi-threaded
        bind(entity, ltest, ltrial)
        lcoeff = localVector(coeff, ltrial)
        lresidual = localResidual(ltest, ltrial, lcoeff)
        accumulateVector(residual, ltest, lresidual)
    return residual
```

```
def accumulateVector(vector, lspace, lvector):
    for dof in range(lspace.size):
        vector[lspace.index(dof)] += lvector[dof]
```

Critical Section

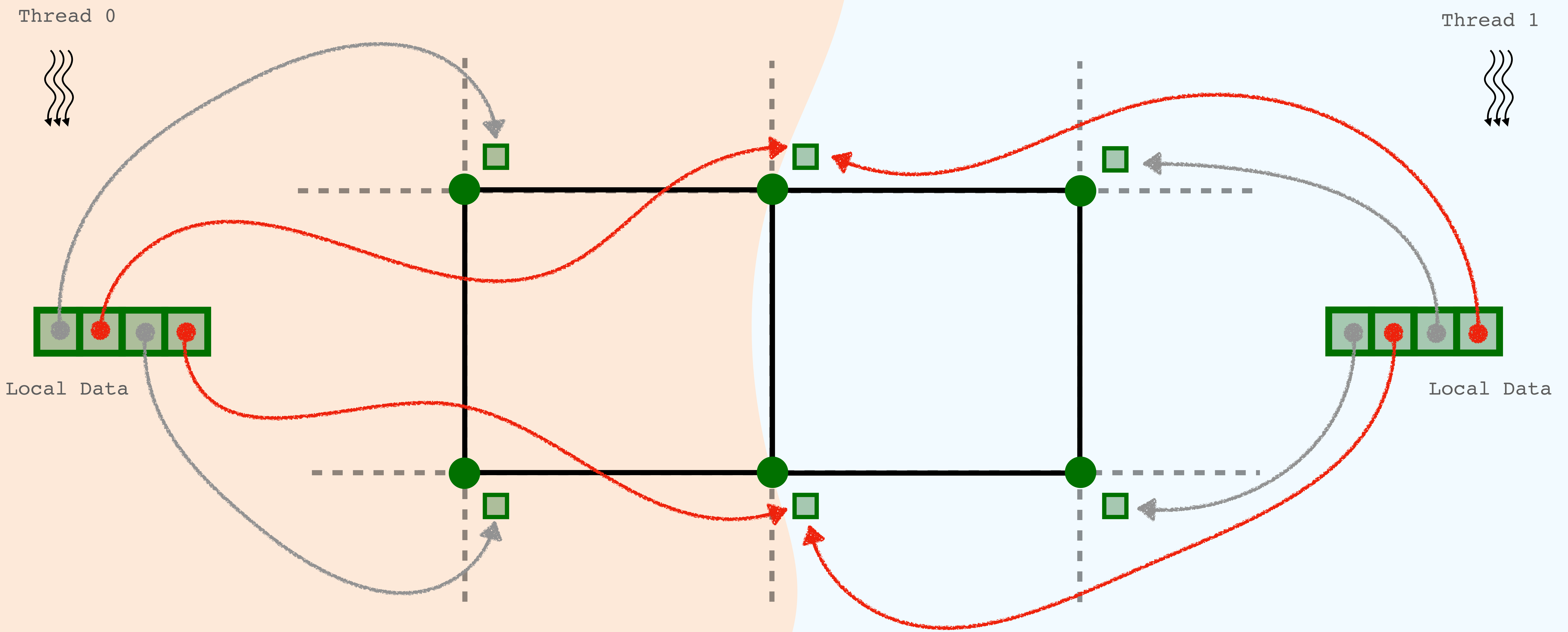
Thread access data as in the sequential case



vector[lspace.index(dof)] += lvector[dof]

Critical Section

Two or more threads may race to access the same global data




```
vector[lspace.index(dof)] += lvector[dof]
```

```
vector[lspace.index(dof)] += lvector[dof]
```

Assembly of Finite Elements

Grid Partition & Work Scheduling

Mask Shared Region

Fine-Grained Locks

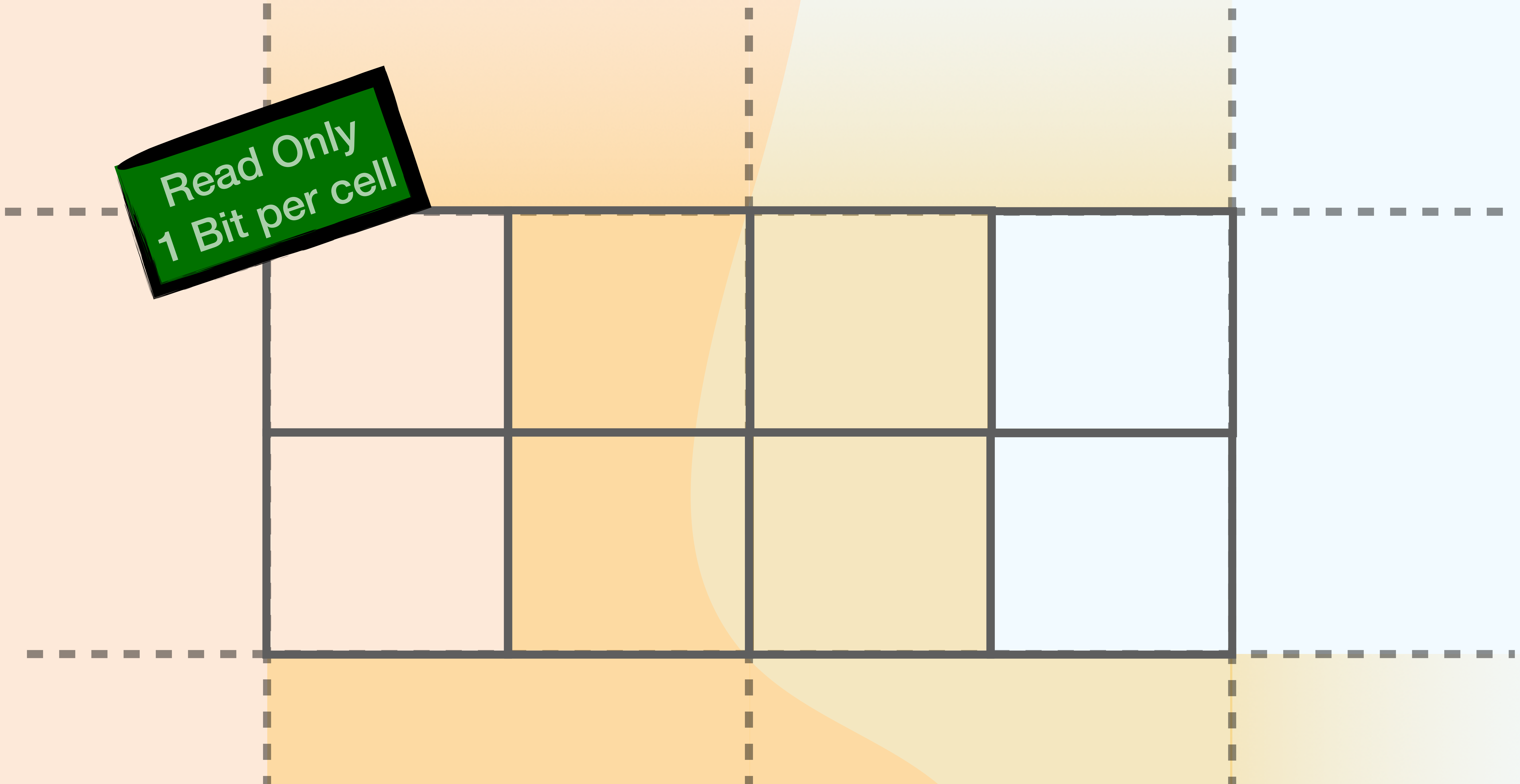
Masking of Critical Section

Shared Region on Grid Partitions

Partition 0

Partition 1

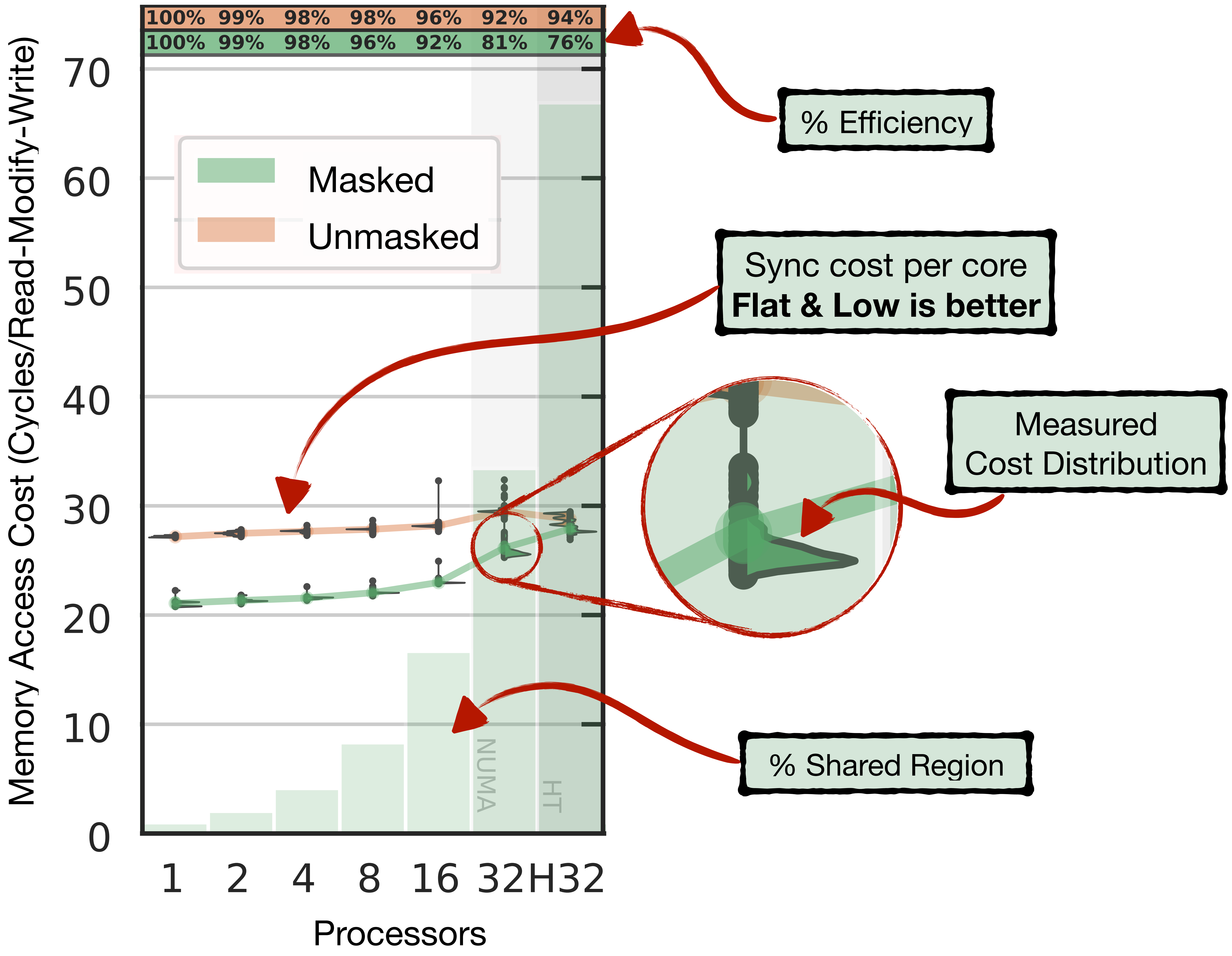
1. Assign a unique owner to each sub-entity
2. Find the shared region on all sub-entities
3. Collect the shared region into back into the cell



Critical Section Micro-Benchmark

A proxy for synchronization cost

```
def benchmark(test, trial, vector):
    for entity in grid_view: # multi-threaded
        bind(entity, ltest, ltrial)
        accumulateVector(vector, ltest)
        unbind(ltest, ltrial)
```



Assembly of Finite Elements

Grid Partition & Work Scheduling

Mask Shared Region

Fine-Grained Locks

Fine-Grained Locks

Same task, different exclusivity modes to access memory

Amount of data exclusive to the lock

`Mutex (std::mutex)`

`Mutex & Batched Buffer`

`Batched Data Lock (std::mutex/N)`

`Grid Entity Locks`

`Atomic Lock (std::atomic & std::atomic_ref)`

Syncronization cost

Fine-Grained Locks

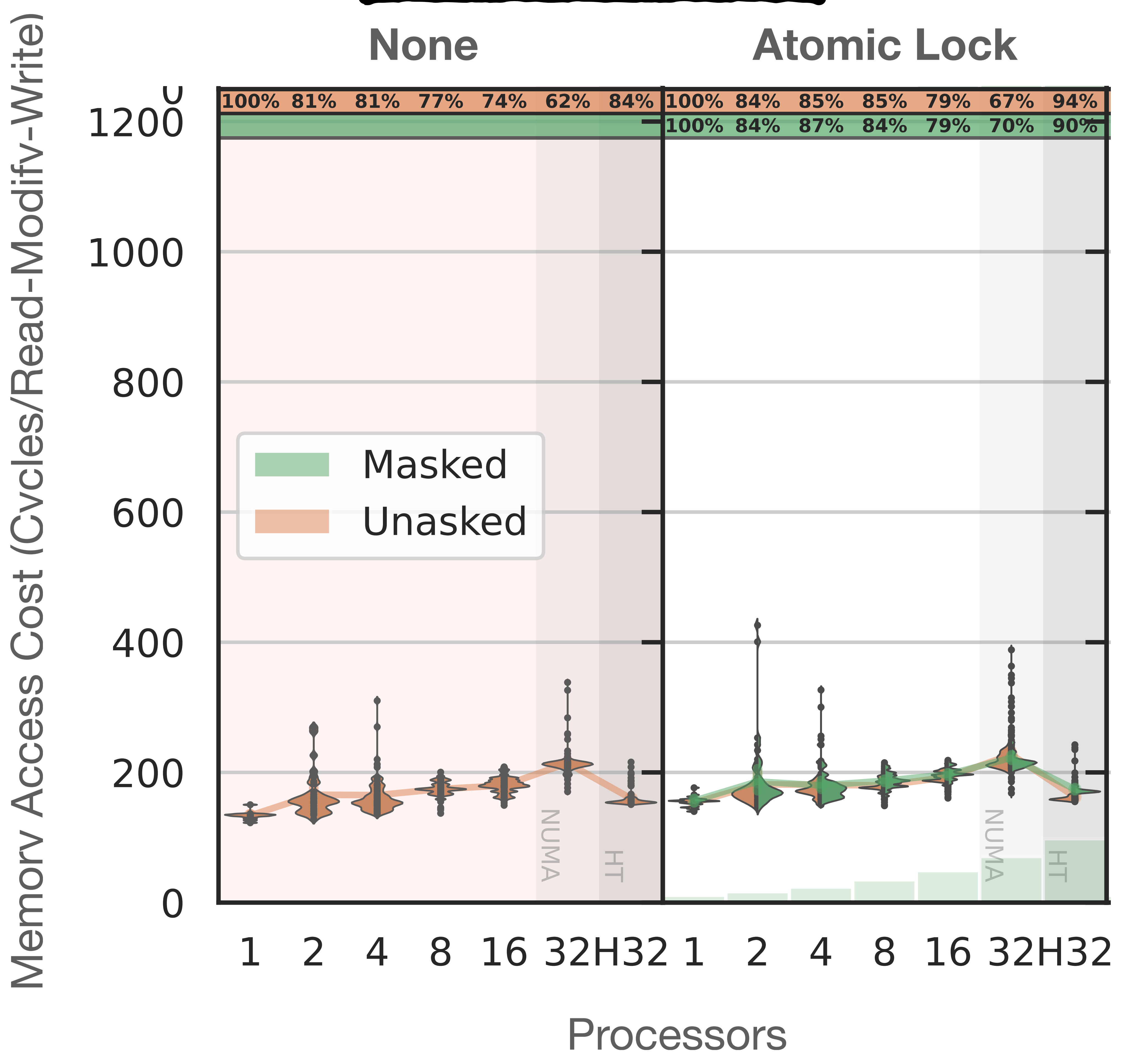
Atomic Lock (std::atomic & std::atomic_ref)

Each data entry has its own Compare & Swap lock

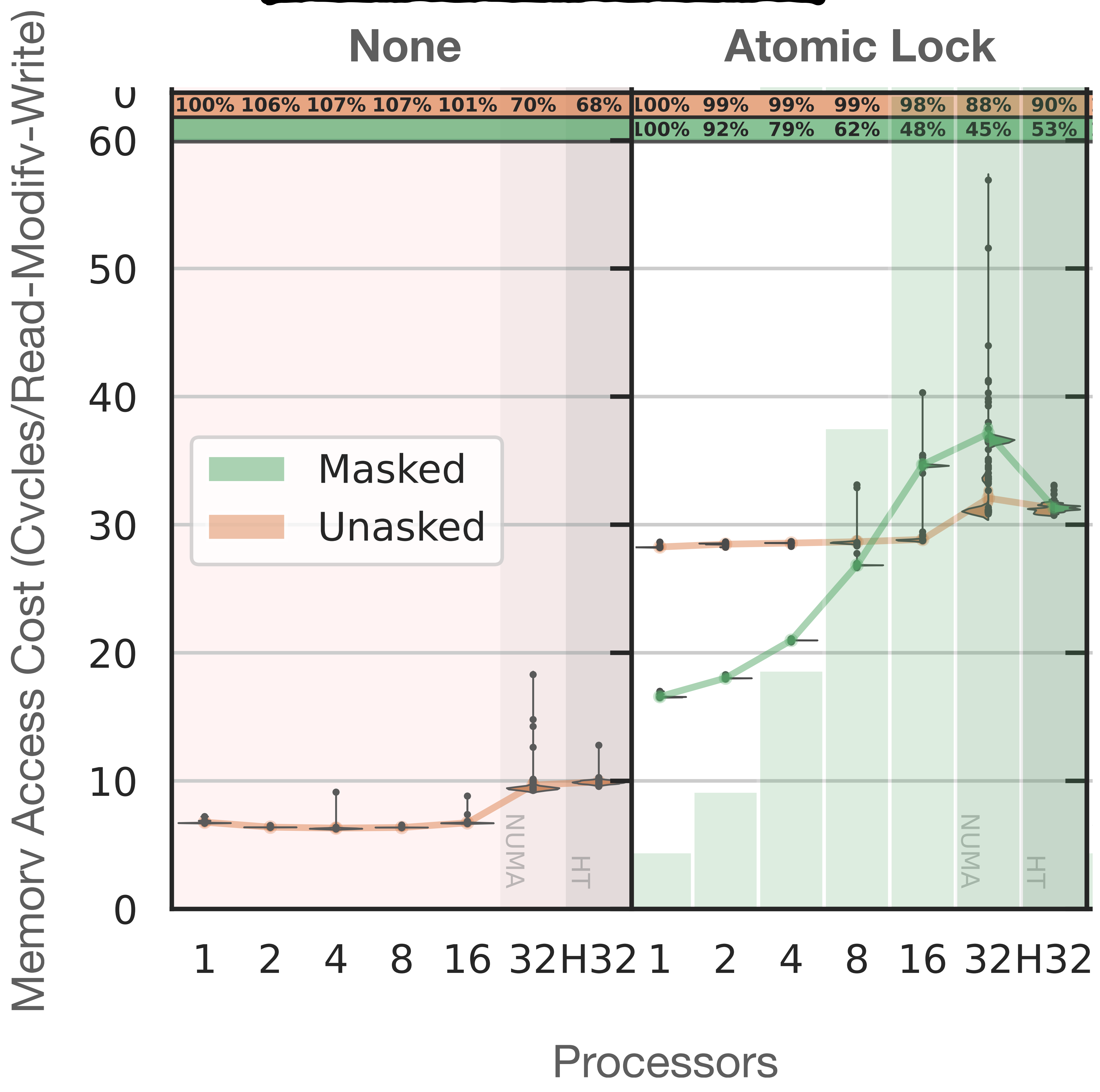
Fine-Grained Locks

`Atomic Lock (std::atomic & std::atomic_ref)`

P1 elements in 2D



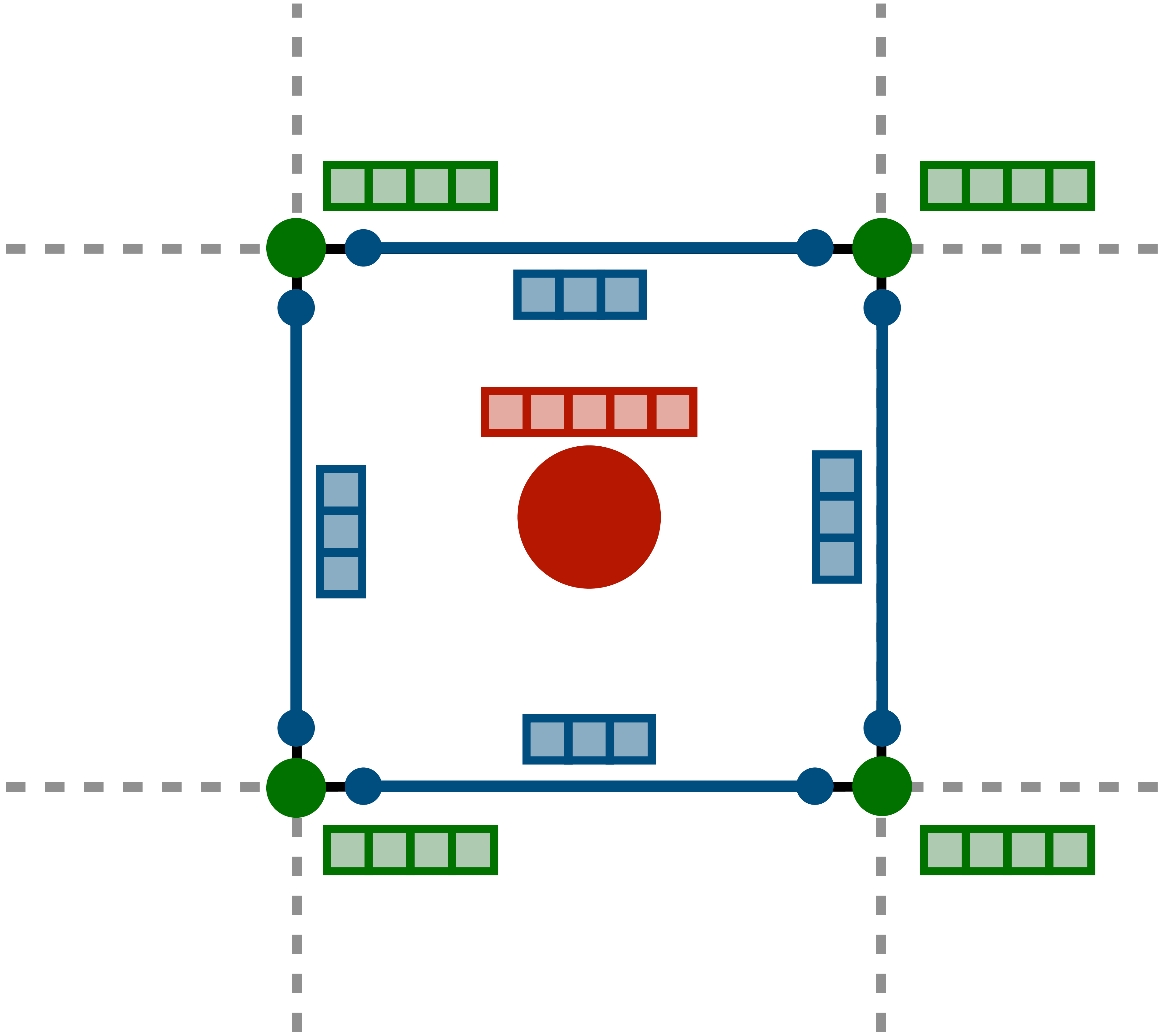
Q5DG elements in 2D



Fine-Grained Locks

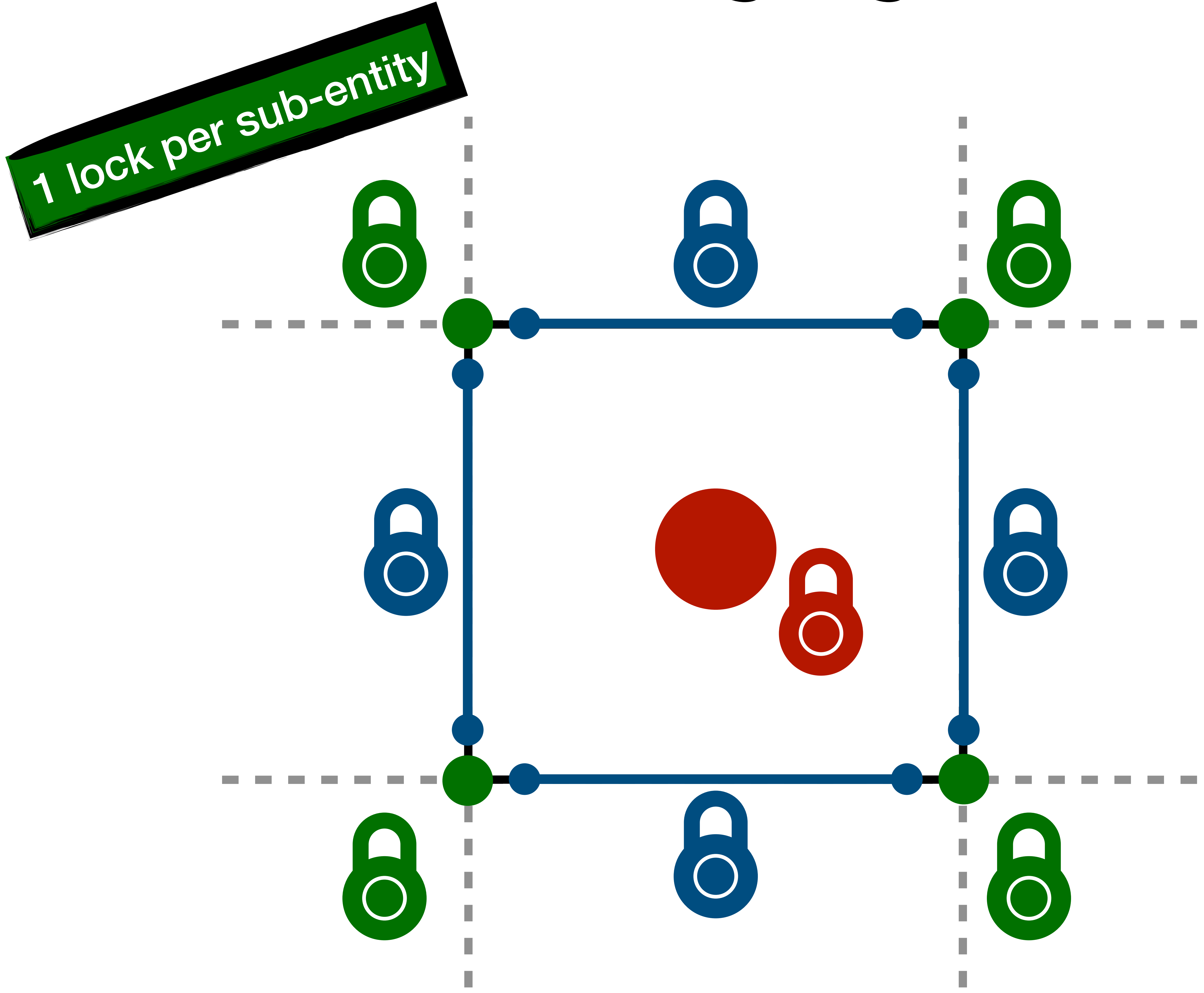
Let's solve the consistency problem locally

```
def accumulateVector(vector, lspace, lvector):
    lspace.lock()
    for dof in range(lspace.size):
        vector[lspace.index(dof)] += lvector[dof]
    lspace.unlock()
```



Fine-Grained Locks

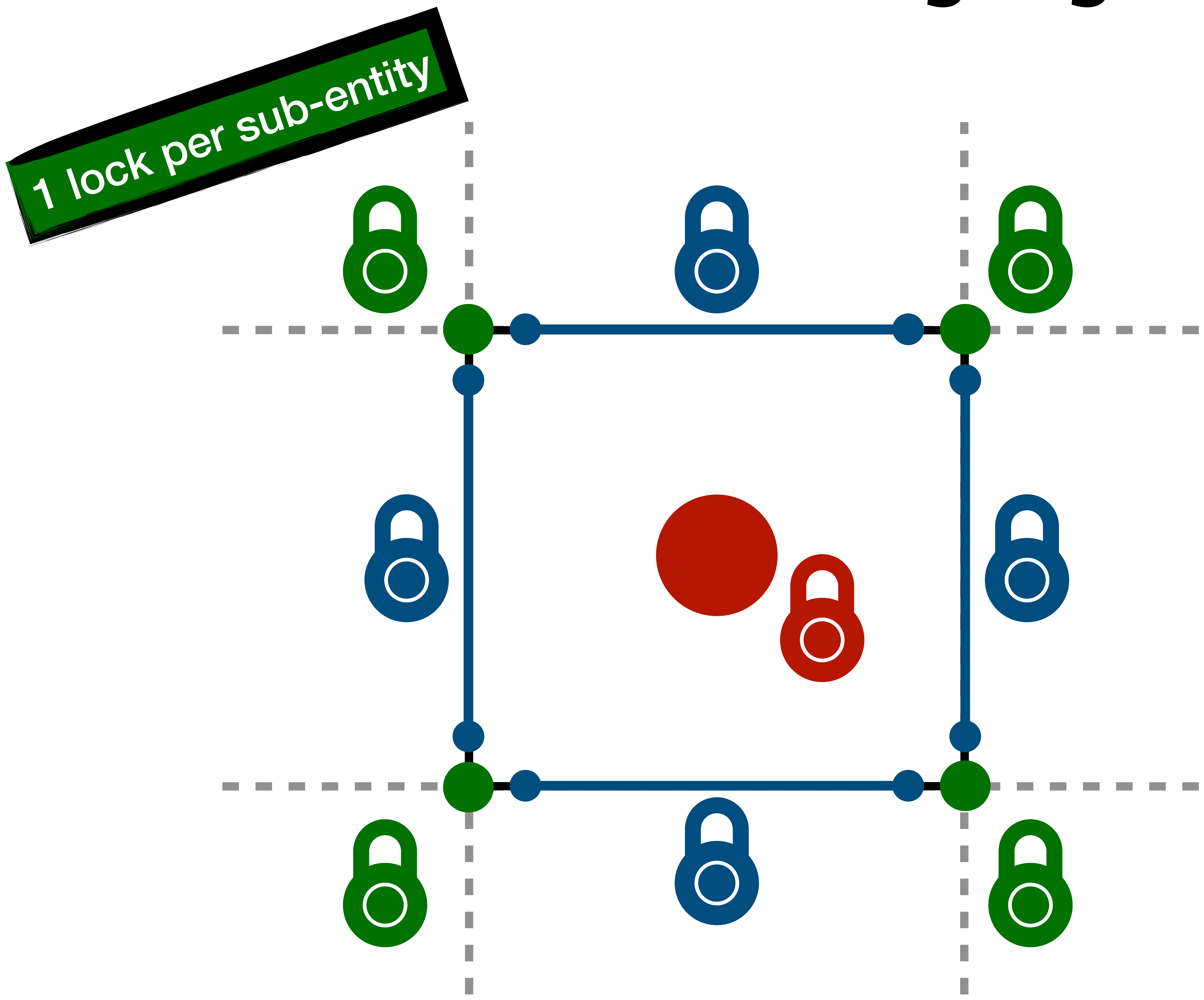
Locking algorithm: Avoiding deadlocks




```
class LocalSpace:
    # true: successful! we have the lock
    # false: failed! another thread has the lock
    def try_lock(self):
        # list of sub-entity padlocks
        padlocks = [🔒,🔒,...,🔒,🔒,...🔒]
        size = len(padlocks)
        # try to lock all the padlocks
        for i in range(size):
            if not padlocks[i].try_lock():
                # release all our locked padlocks
                for j in range(size-i-1):
                    padlocks[j].unlock()
                return False
        return True
```

Fine-Grained Locks

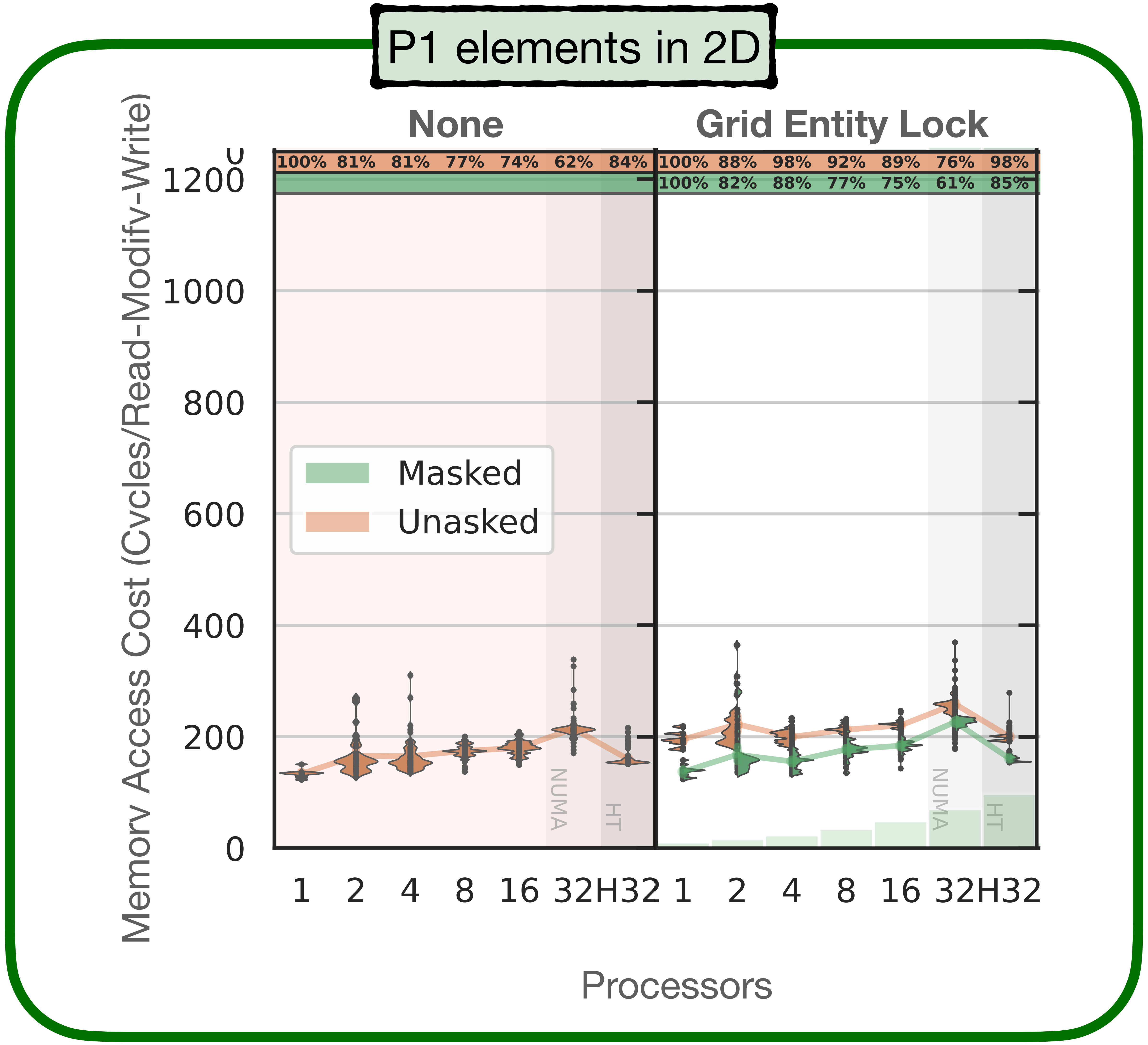
Locking algorithm: Spin Lock

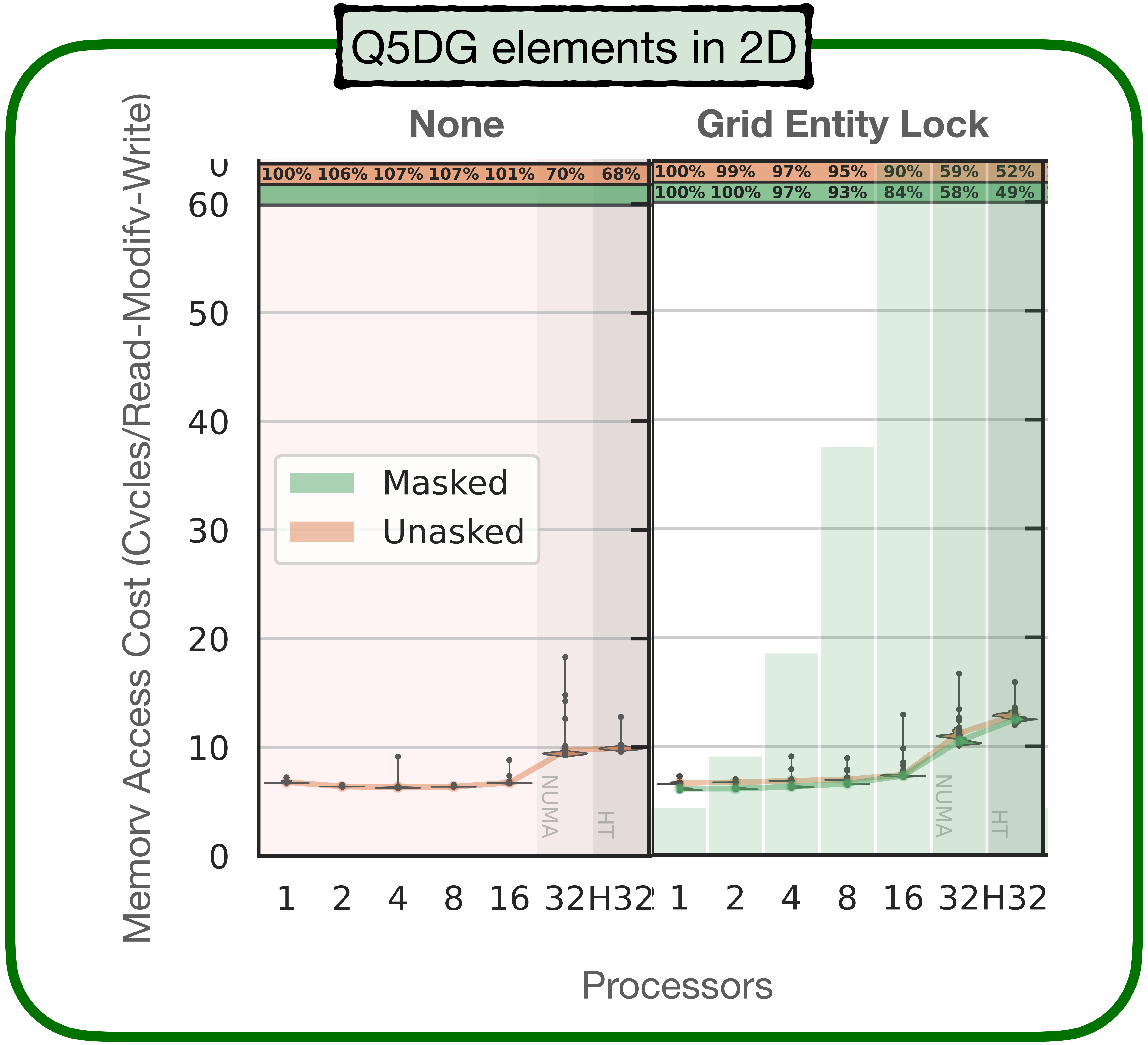



```
class LocalSpace:
    def lock(self):
        # spin until we acquire all the padlocks
        while(not self.try_lock()):
            pass
```

Fine-Grained Locks

Grid Entity Locks





Shared Memory vs Private Memory

Same task, different spatial modes to access memory

Benchmark of a more realistic HPC case

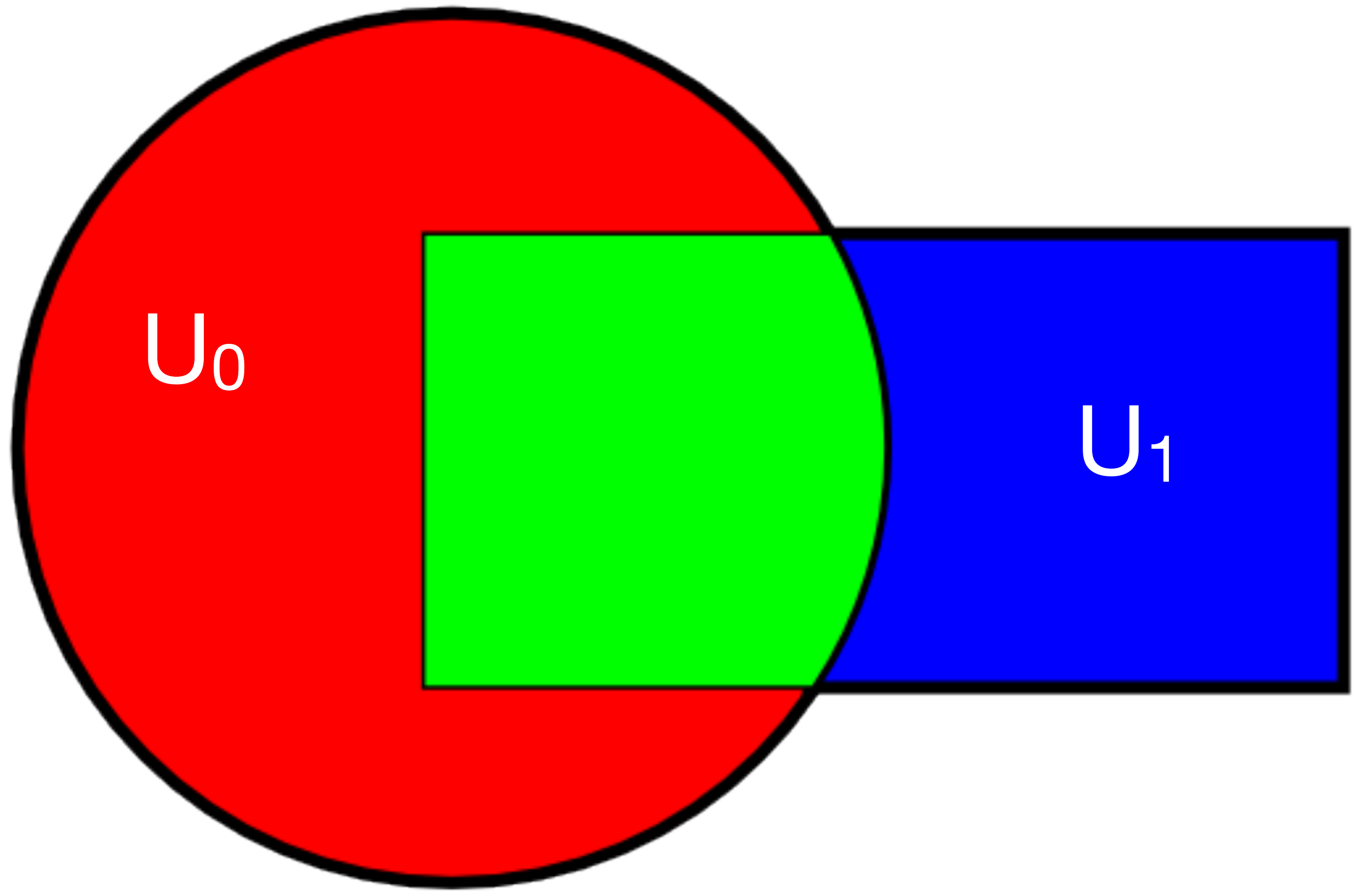
VectorBitSpinLock+TBB+Unmasked

- Reaction-Diffusion Equation
  - Structured grid in 3D
  - Discontinuous Galerkin with Interior Penalty
  - Assembly of a Residual Operator (Representative of Matrix-Free workload)
- AMD EPYC 7713 Milan
  - 64 Cores, 1 Socket
  - 1 Numa Node Per Socket (NPS=1)
- SIMD Vectorized Kernel
  - ~60% of Peak Performance
  - ~15 Arithmetic Intensity

Shared Memory vs Private Memory

How to measure throughput?

- **Issue**: Private and Shared memory approaches may not need the same amount of DOFs to solve the *same* problem.



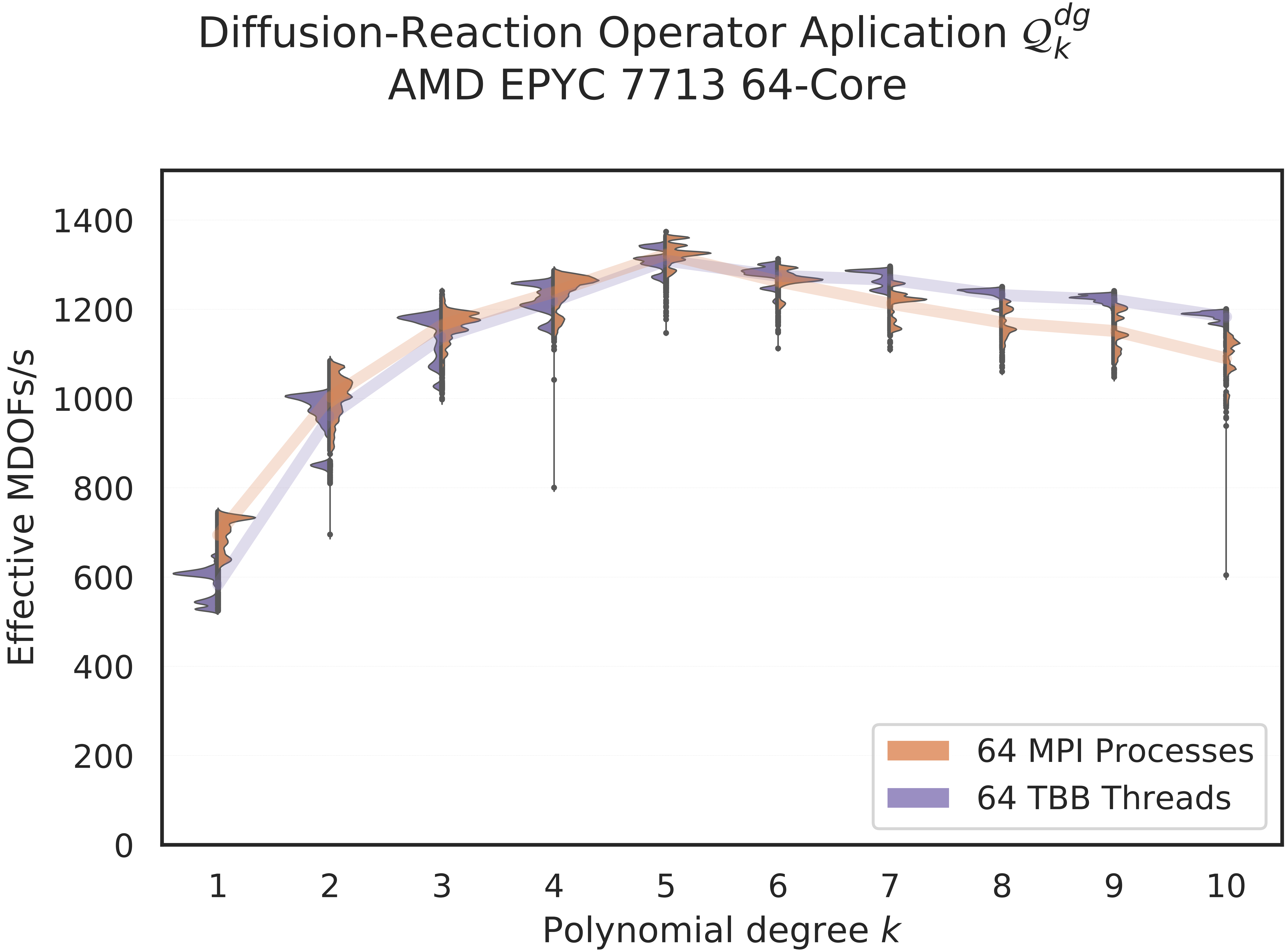
Total Degrees of Freedom

$$\overbrace{DOFs}^{\text{Total Degrees of Freedom}} := \sum_{p=0}^{P} dim(U_p)$$

$$\underbrace{EDOFs}_{\text{Effective Degrees of Freedom}} := dim\left(\cup_{p=0}^{P} U_p \right)$$

Effective Degrees of Freedom

Shared Memory vs Private Memory



Conclusions

- Entity level mutual exclusive locks are robust and scalable for Finite Elements.
- Shared region on grid partitions can amortize synchronization costs effectively.
- TBB work stealing can hides latency and unbalance issues on high core counts.

Thanks for your Attention

Question?