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Calico: Rethinking the Language / Runtime-System Boundary

Ross McIlroy, Steven Smith
and Tim Harris

Ubiquitous Multi-Core

- Traditionally parallelism was confined to HPC systems
- Multi-core now pervades commodity systems
  - Consumer applications are being forced to turn to parallelism to increase performance
- Techniques employed by the HPC community do not necessarily carry over
  - Don't "own" the machine
  - Multiple competing applications
  - Different latency / throughput priorities
  - Workload typically much shorter and less predictable

Calico

- A low-level parallel runtime system
  - Support C / C++ applications
- Tackle challenges in future architectures
  - Heterogeneous Cores
  - Changing core-counts (interactive apps, energy saving, dynamic core reconfiguration)
  - Non-cache coherency
- Task-based, fork-join programming model
  - Programmer specifies what can be run in parallel
  - Runtime system decides what is run in parallel
  - Integrate with AC / THC, provide parallelism as well as asynchrony

Calico Programming Model

```
do {
    async msg_send(core 1, “Computing Forces”);
    par fluid                                  ls, range);
} finish;
```

Spawn a bunch of parallel tasks that can be run across multiple cores

Wait for parallel **and** async tasks to complete before continuing

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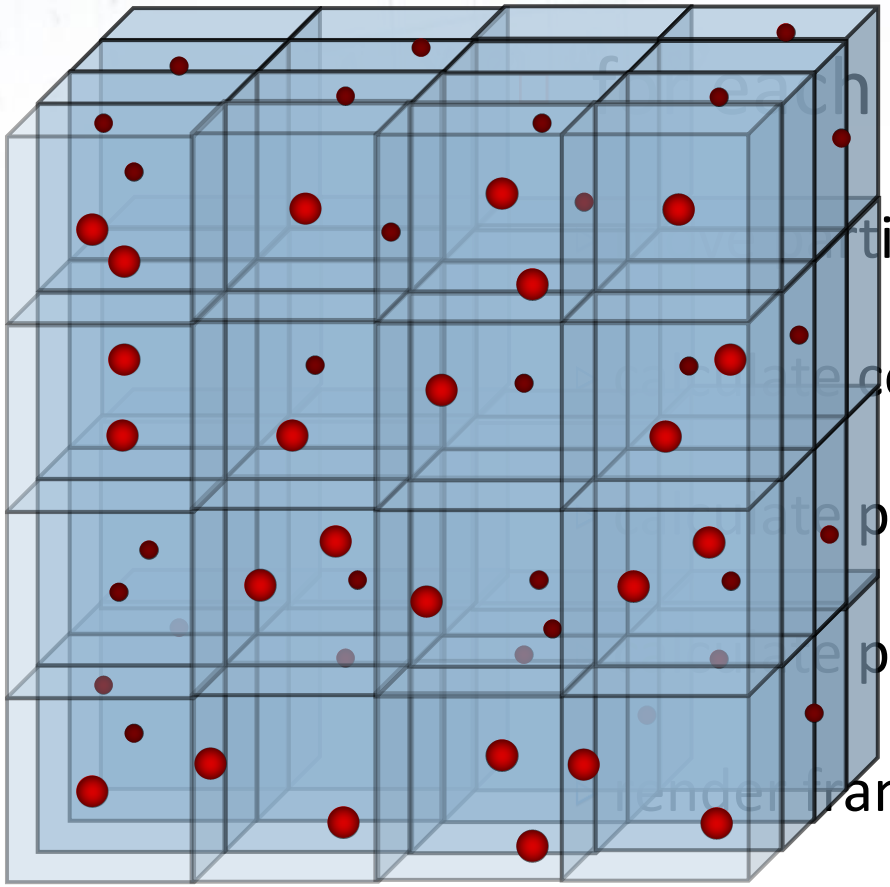
FluidAnimate



for each frame

Invalidate particles to correct cell

Calculate cell density

Calculate particle forces

Calculate particles position

Render frame

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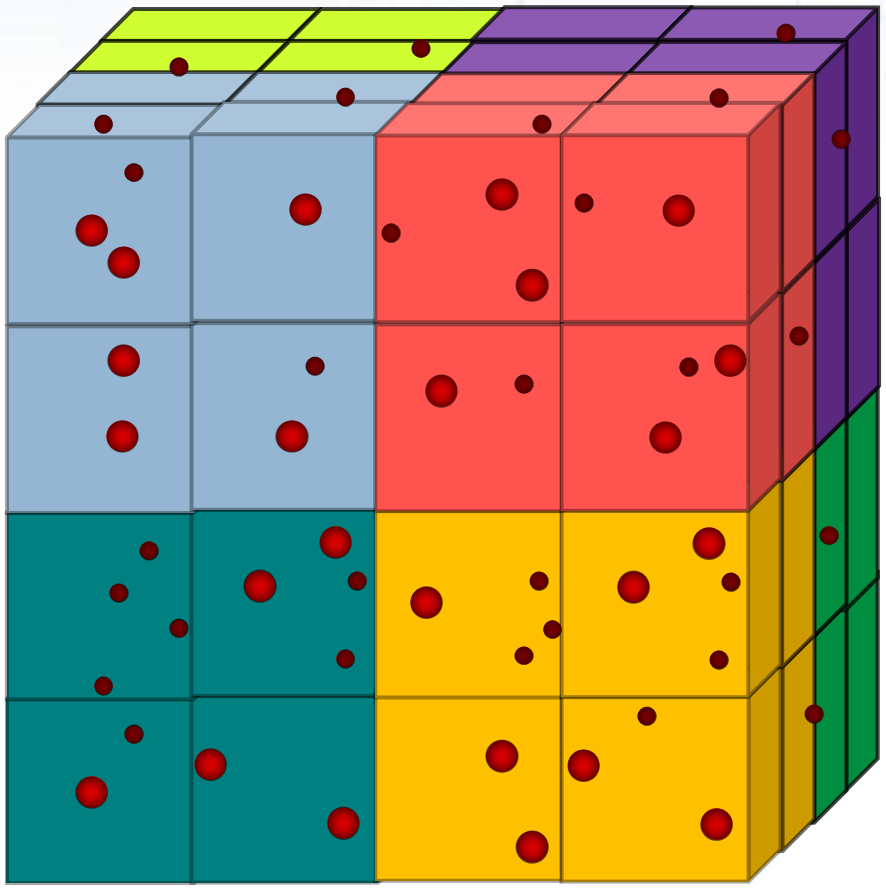
Static Partitioning



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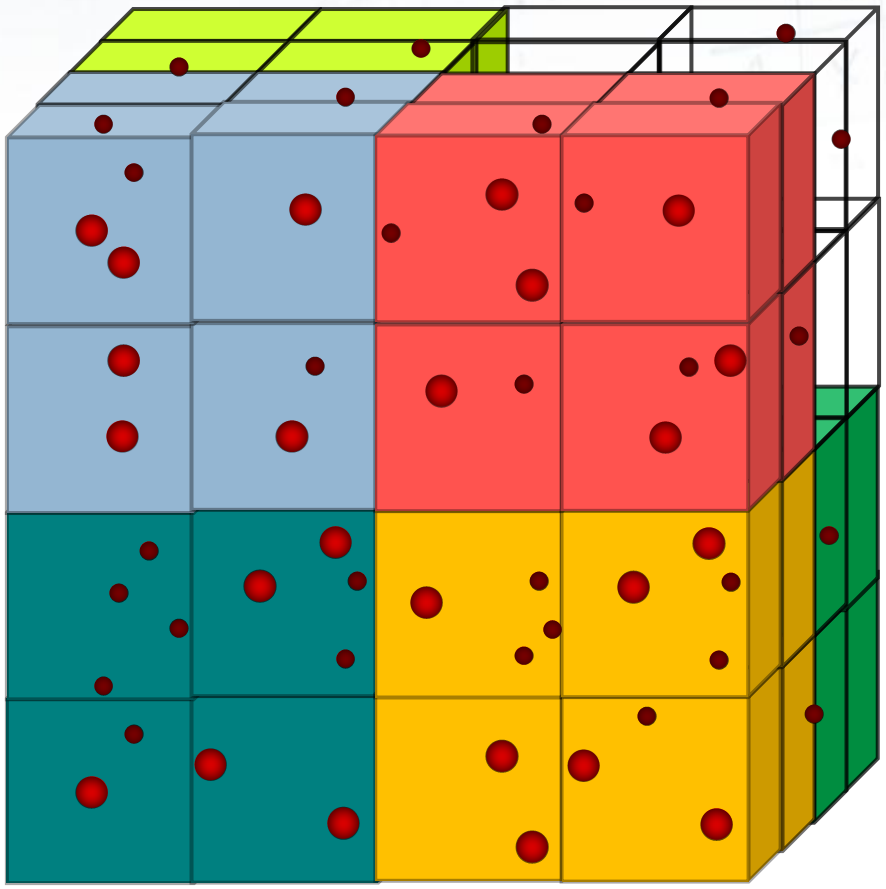
Microsoft Research

Static Partitioning



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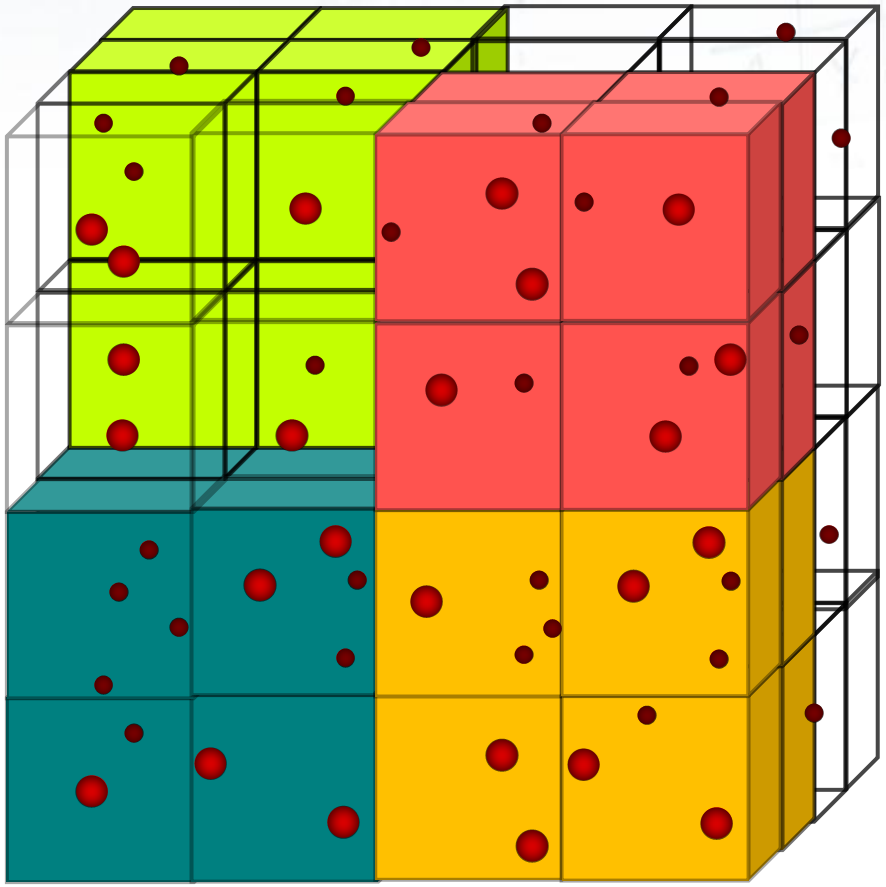
Static Partitioning

- Problem: Uneven workload



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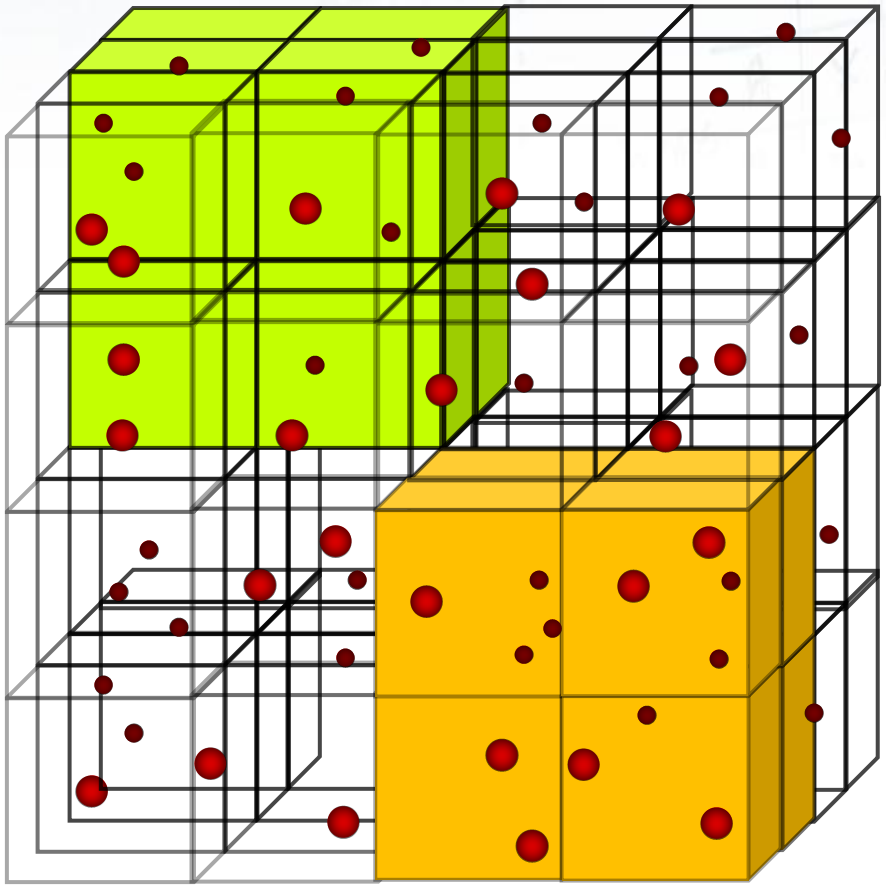
Static Partitioning

- Problem: Barrier Synchronization



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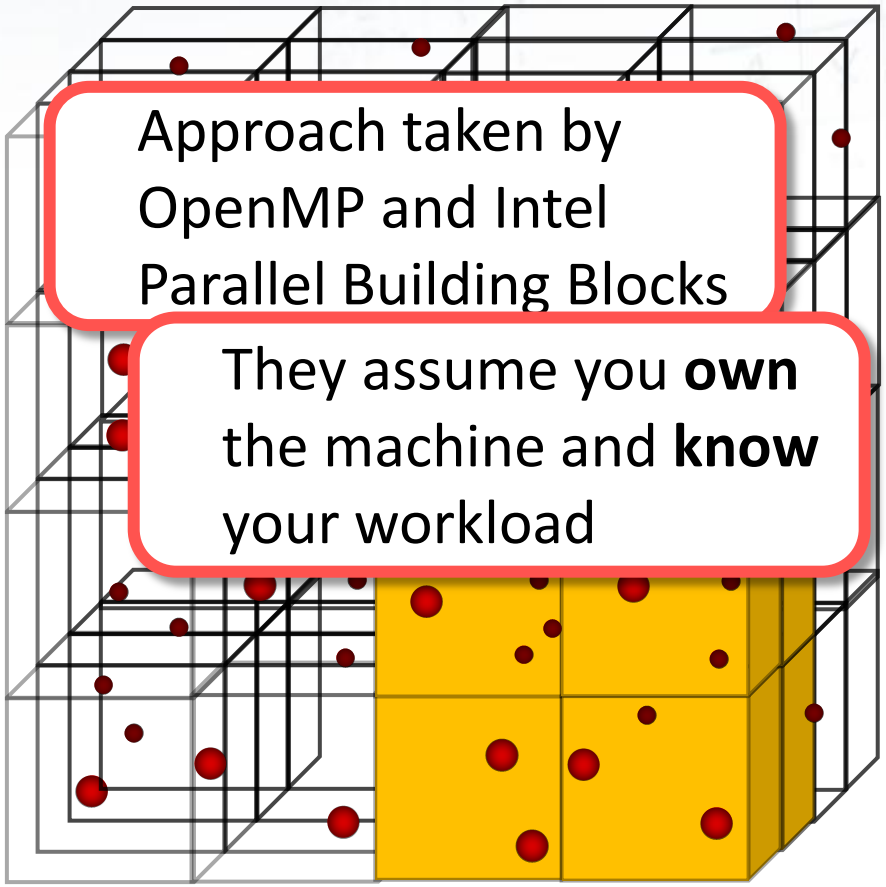
Static Partitioning

- Problem: Thread Preemption



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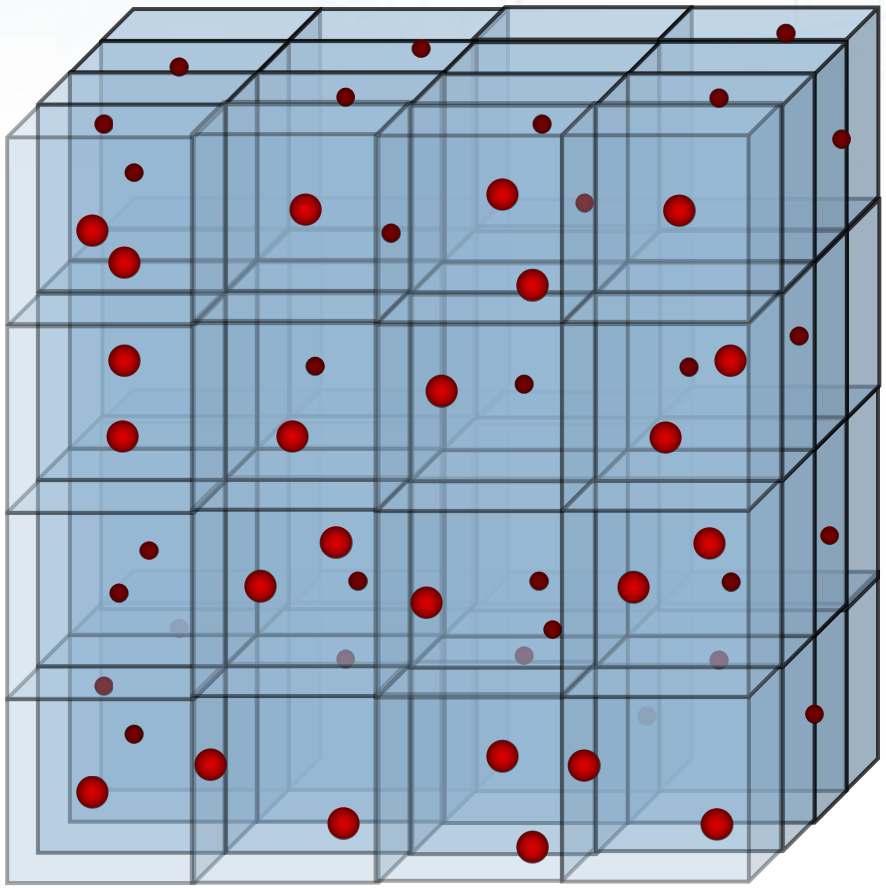
Dynamic Partitioning (Work-Stealing)



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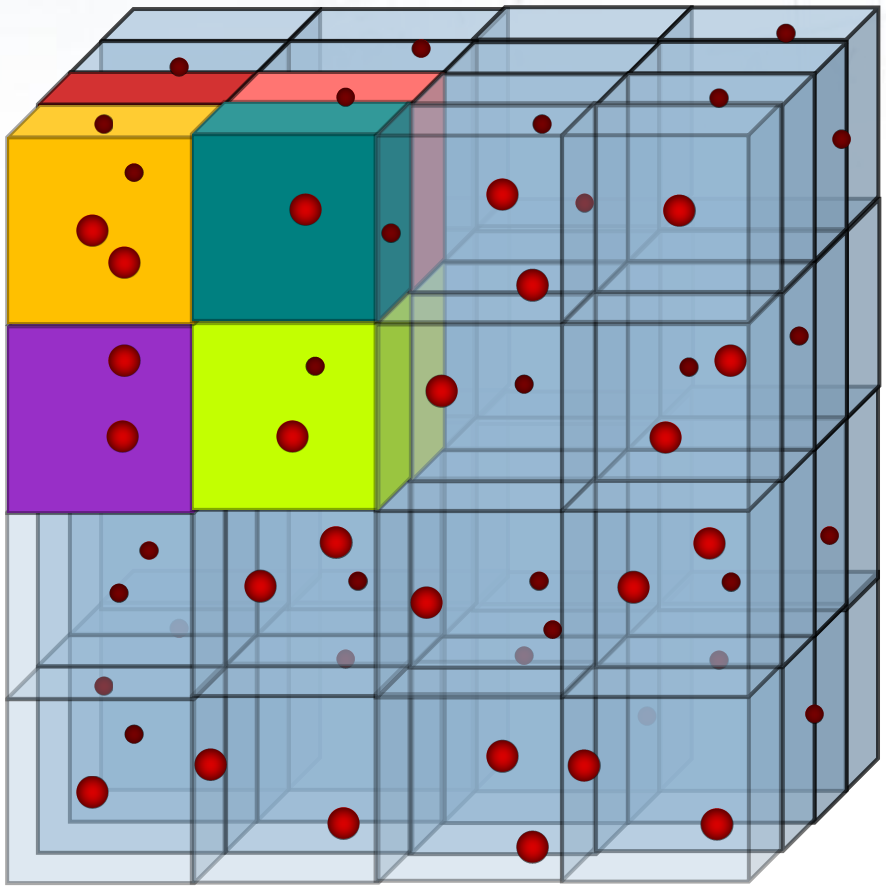
Work-Stealing



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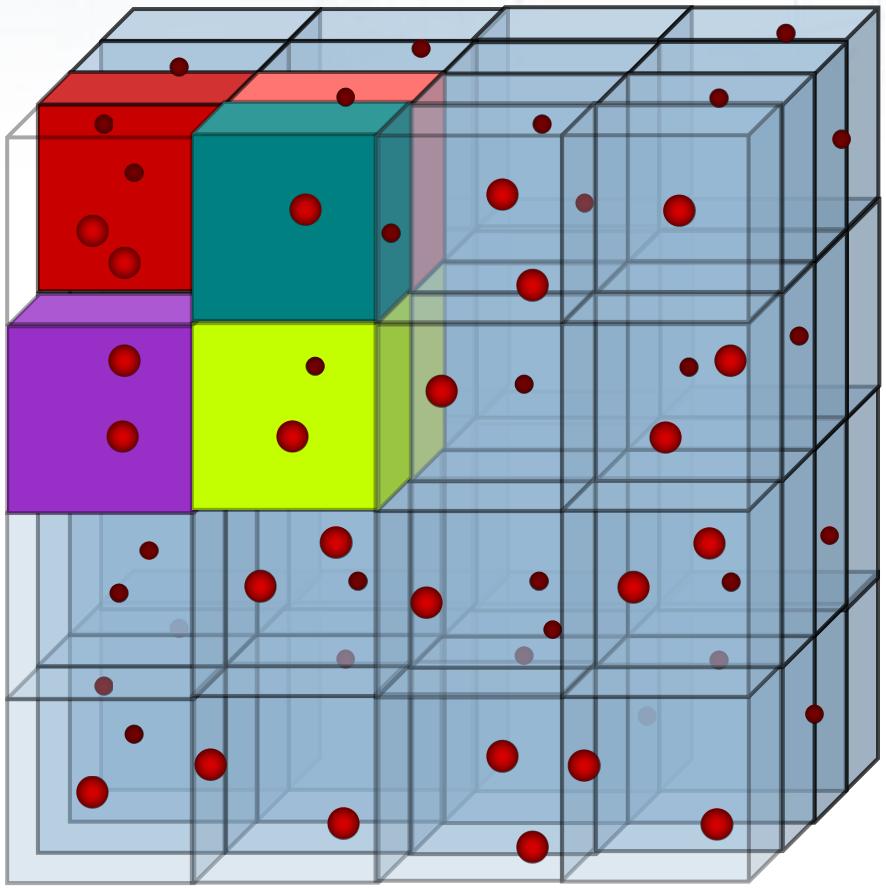

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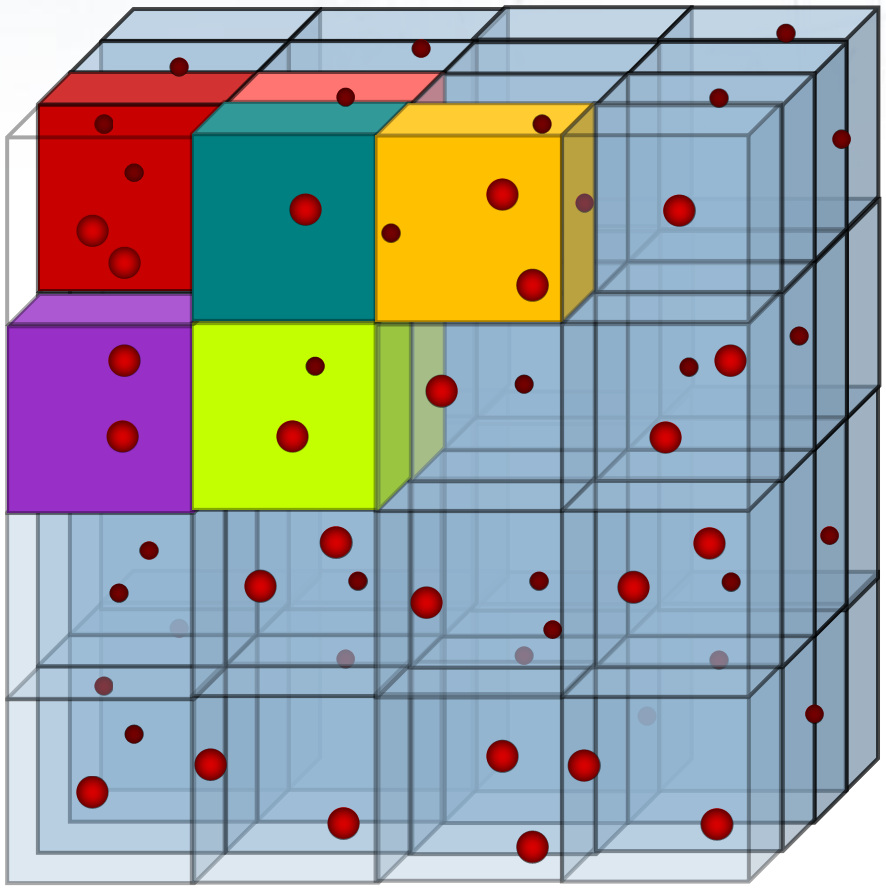

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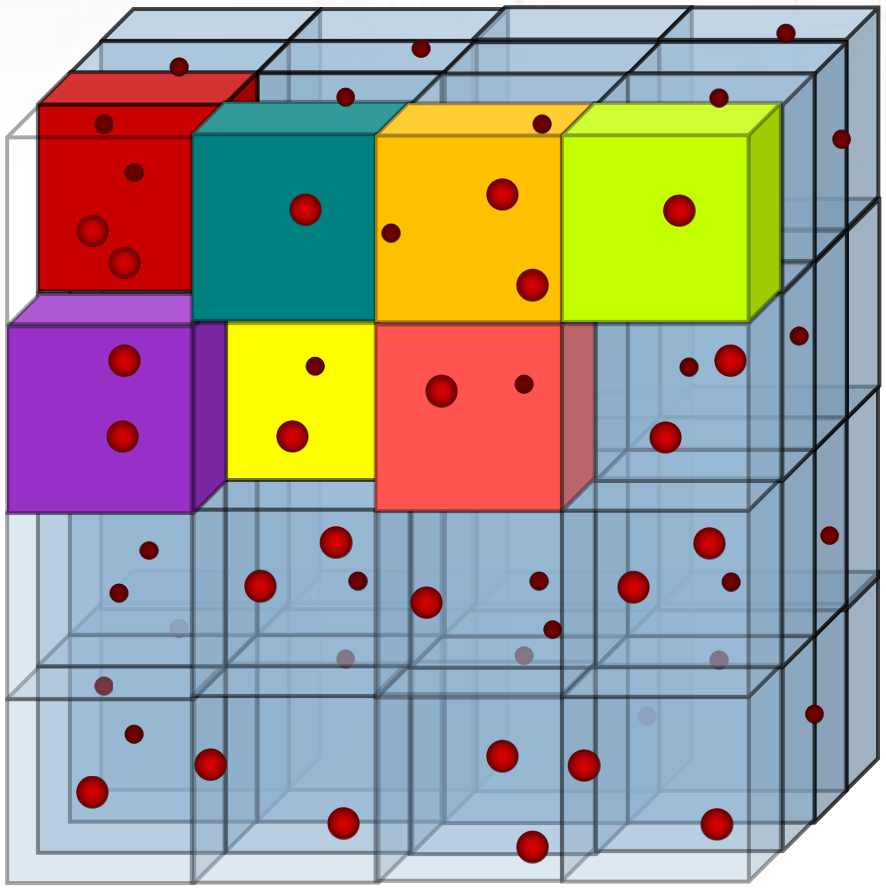

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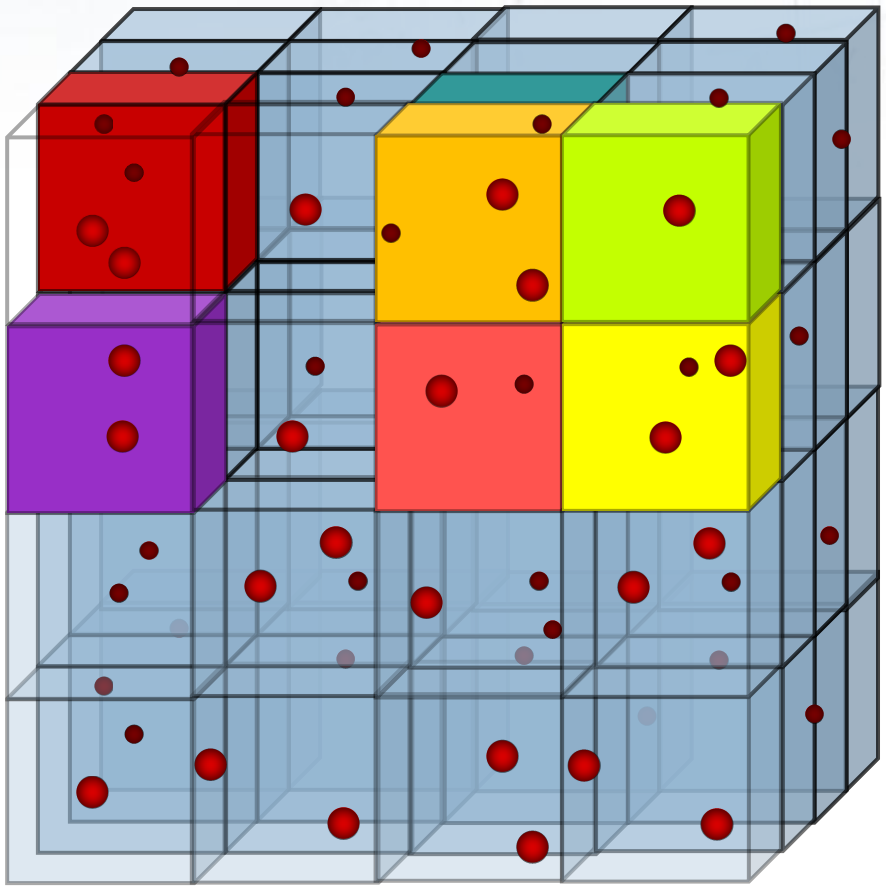

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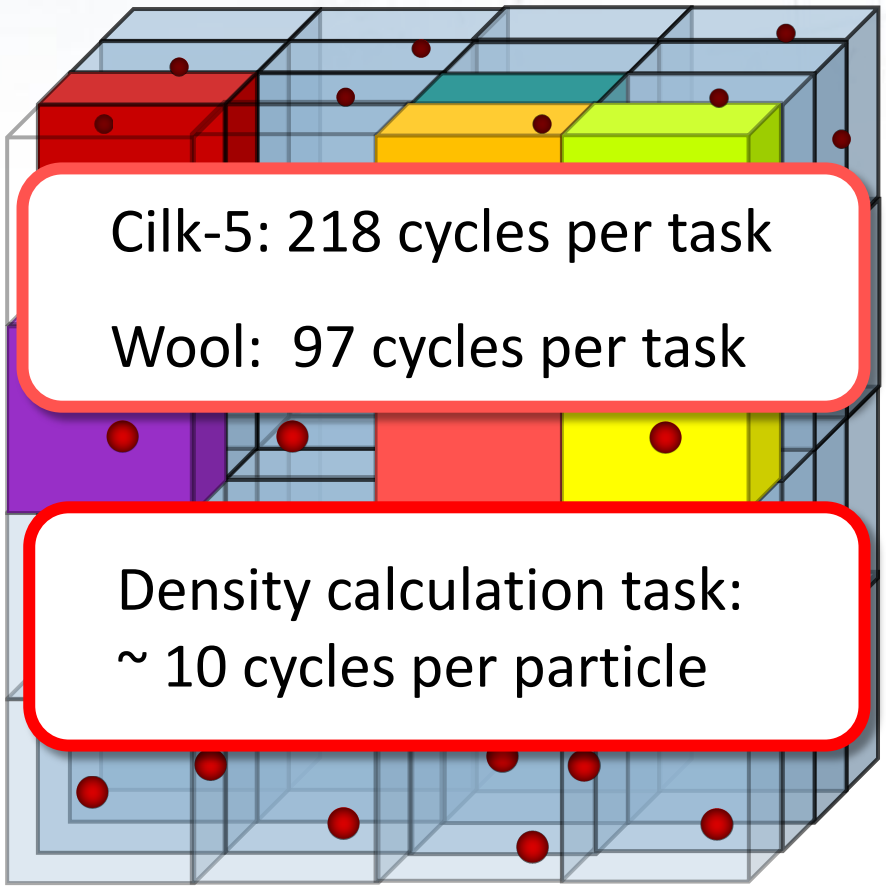
Dynamic Partitioning (Work-Stealing)

- Problem: Spawn / Sync Overhead



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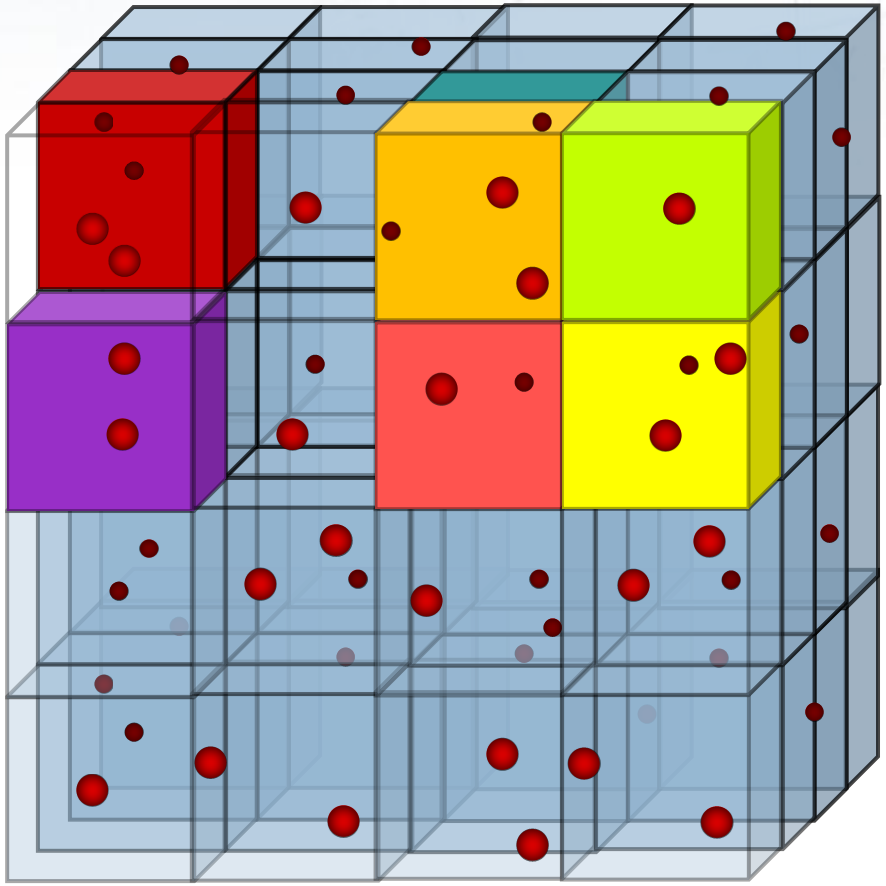
Dynamic Partitioning (Work-Stealing)

- Problem: Cache Locality



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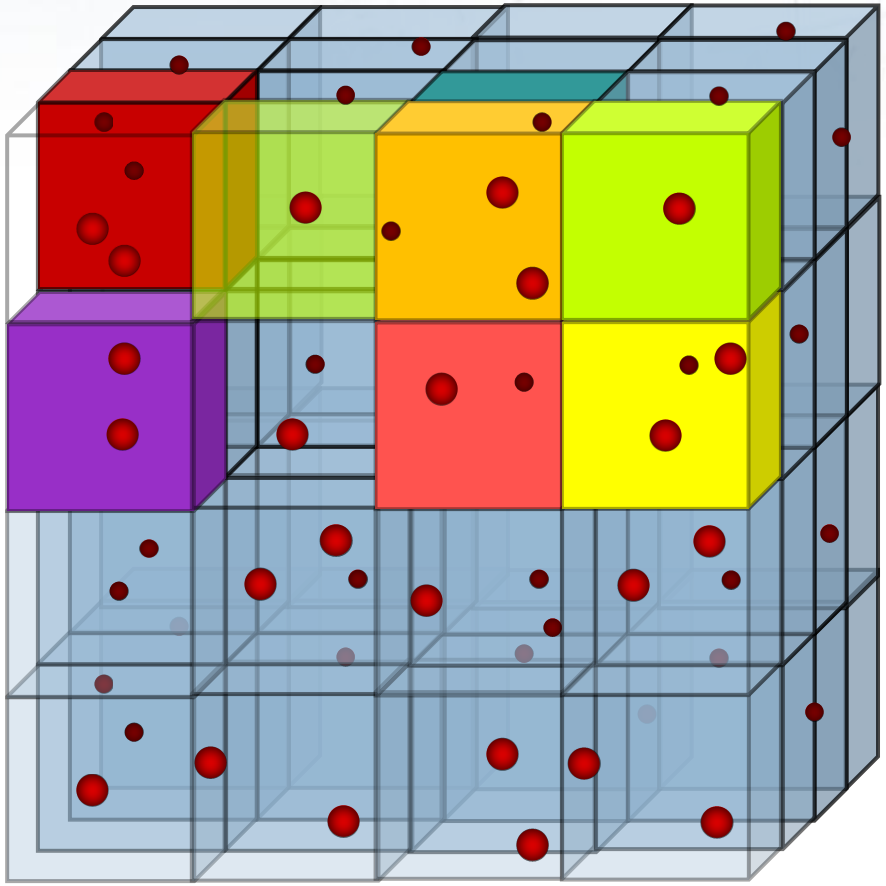

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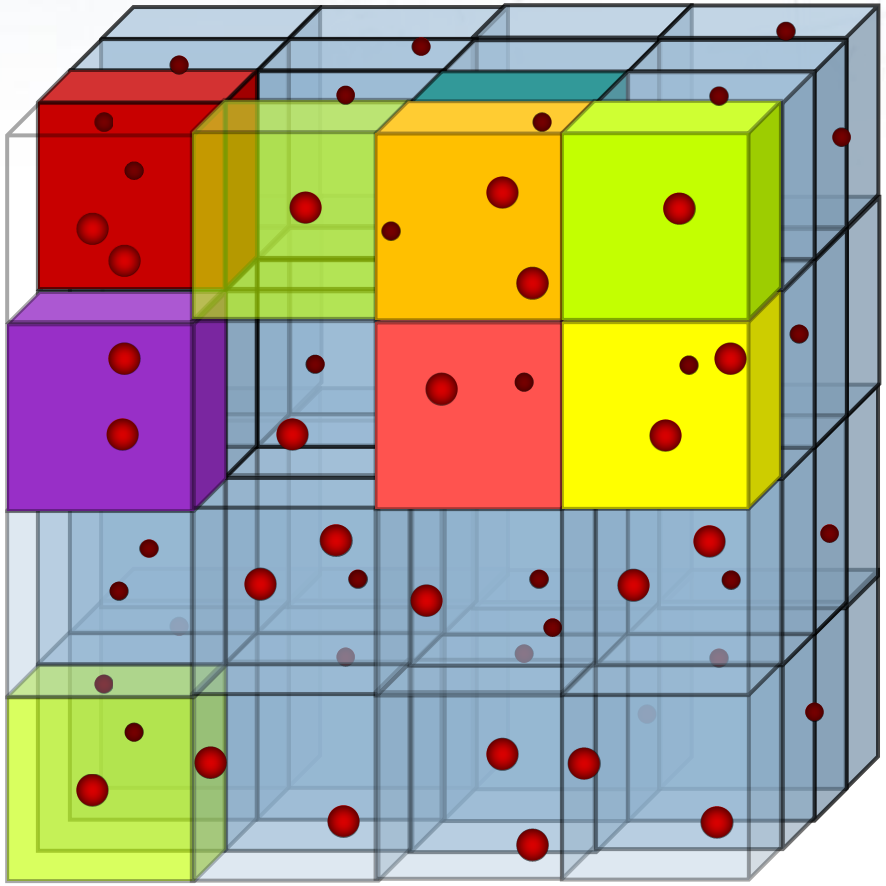

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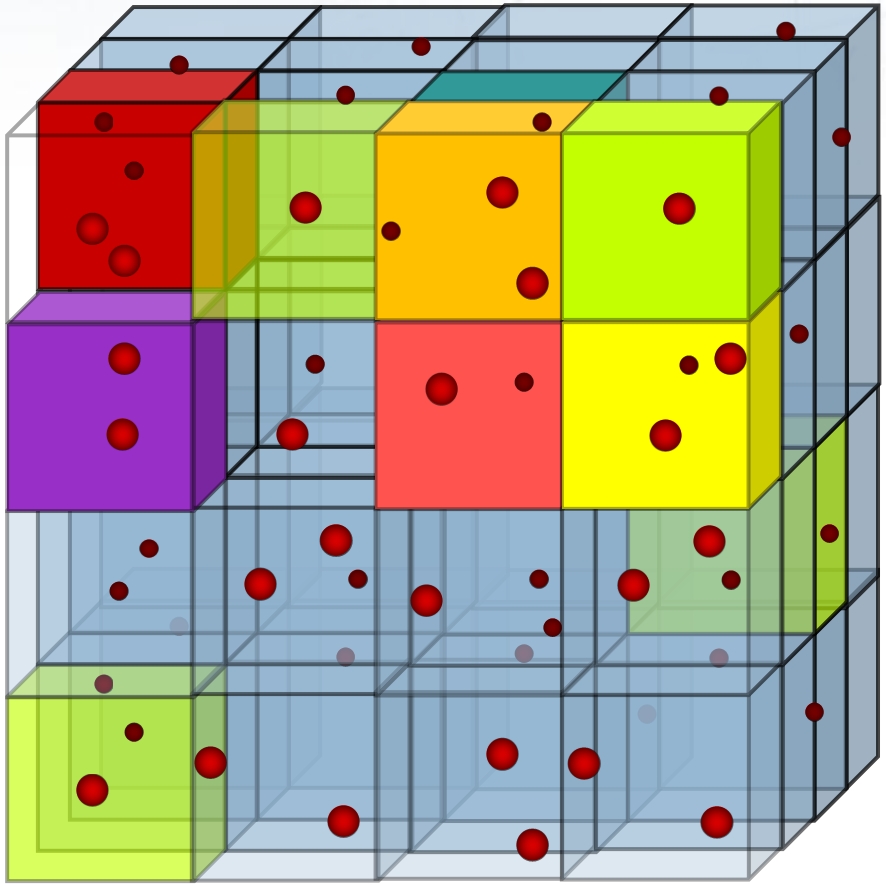

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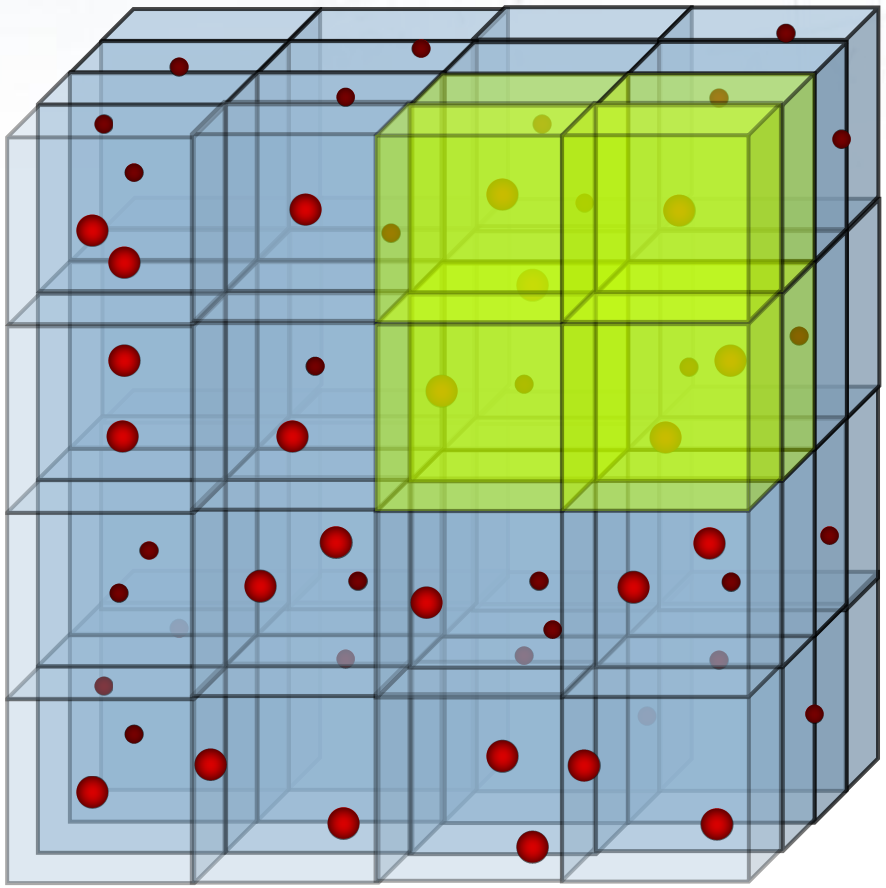

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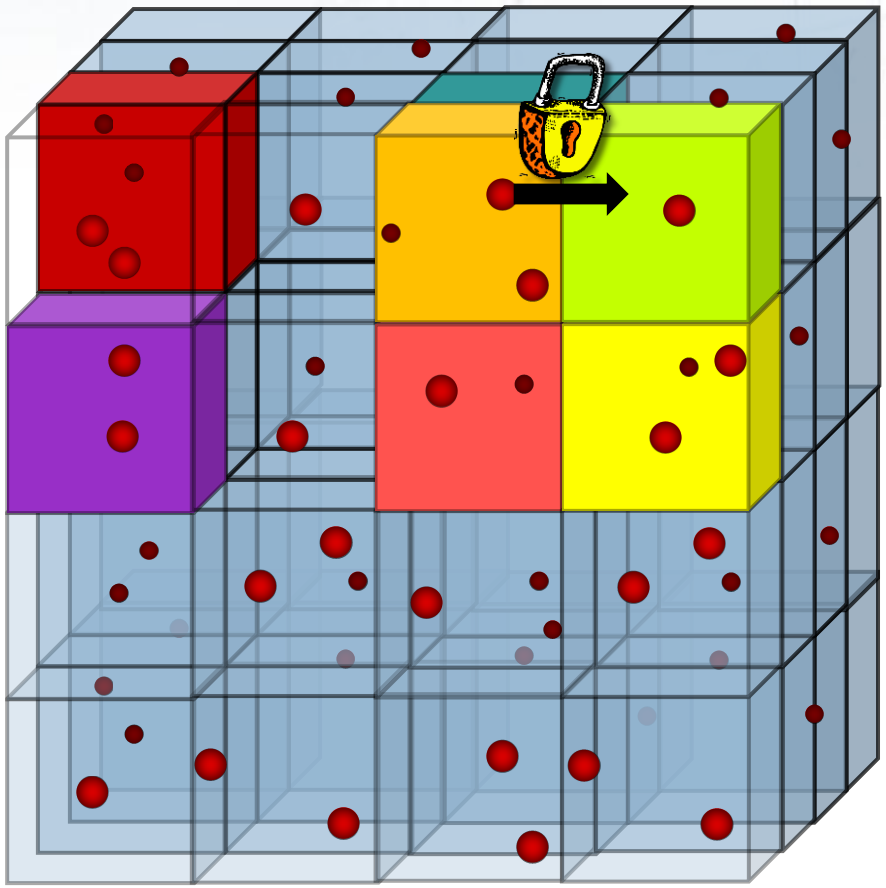
Dynamic Partitioning (Work-Stealing)

- Problem: Data Synchronization



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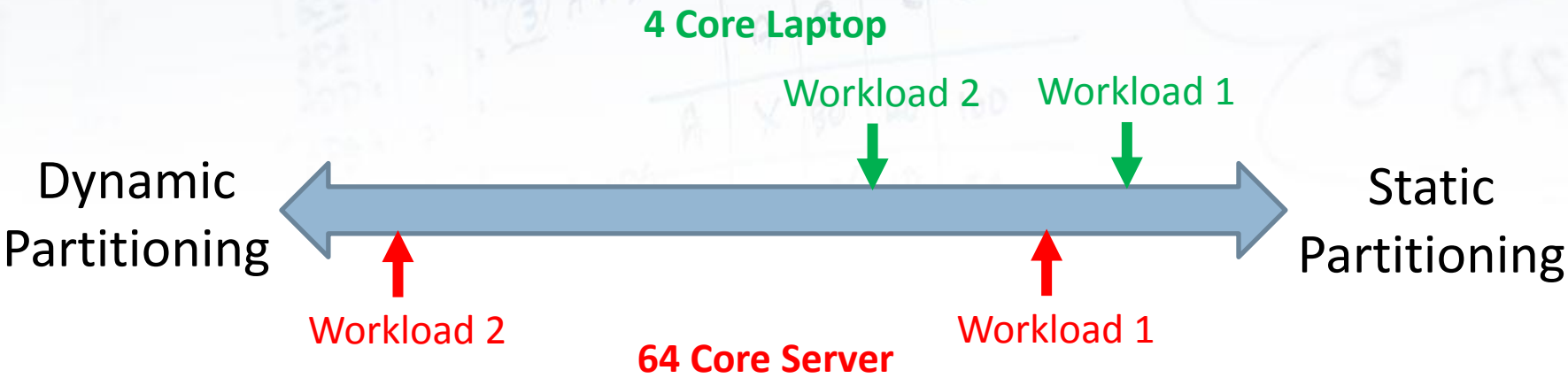
Space-Time Continuum



- **Disciplined partitioning** programming model
  - Flexible enough to enable movement on this continuum dynamically **at runtime**
  - Runtime system controls where
    - Is enough work for available cores? If not, repartition work
  - Application controls how
    - Parameterise how data is partitioned
    - Decide whether data-synchronisation is necessary

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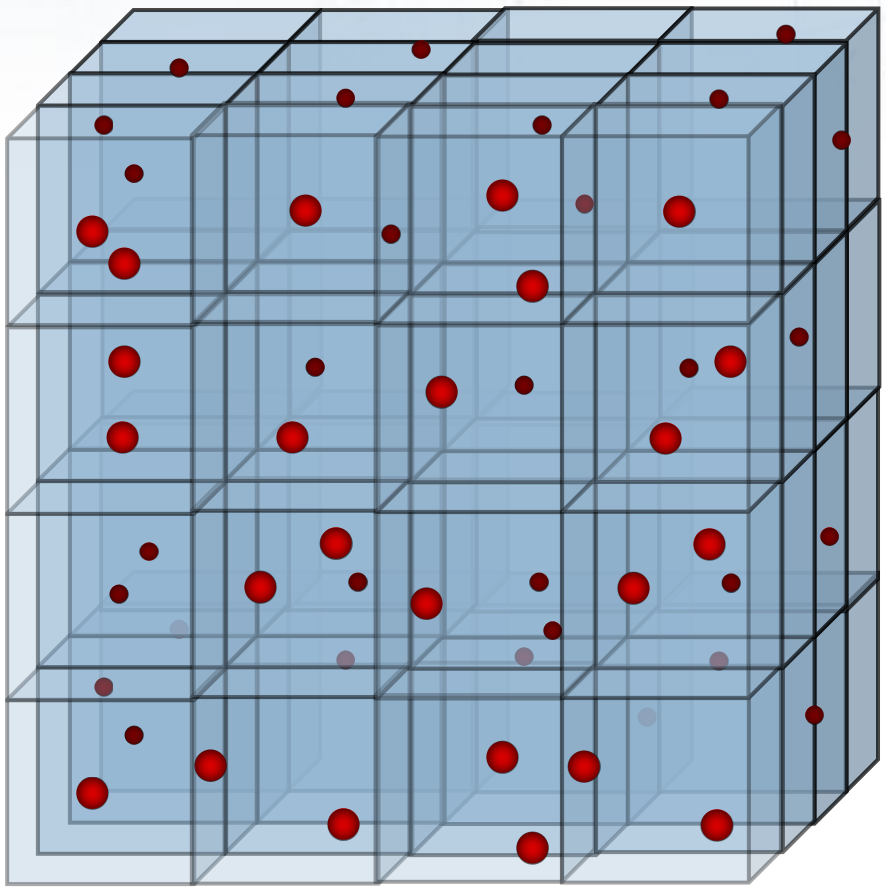
Disciplined Partitioning



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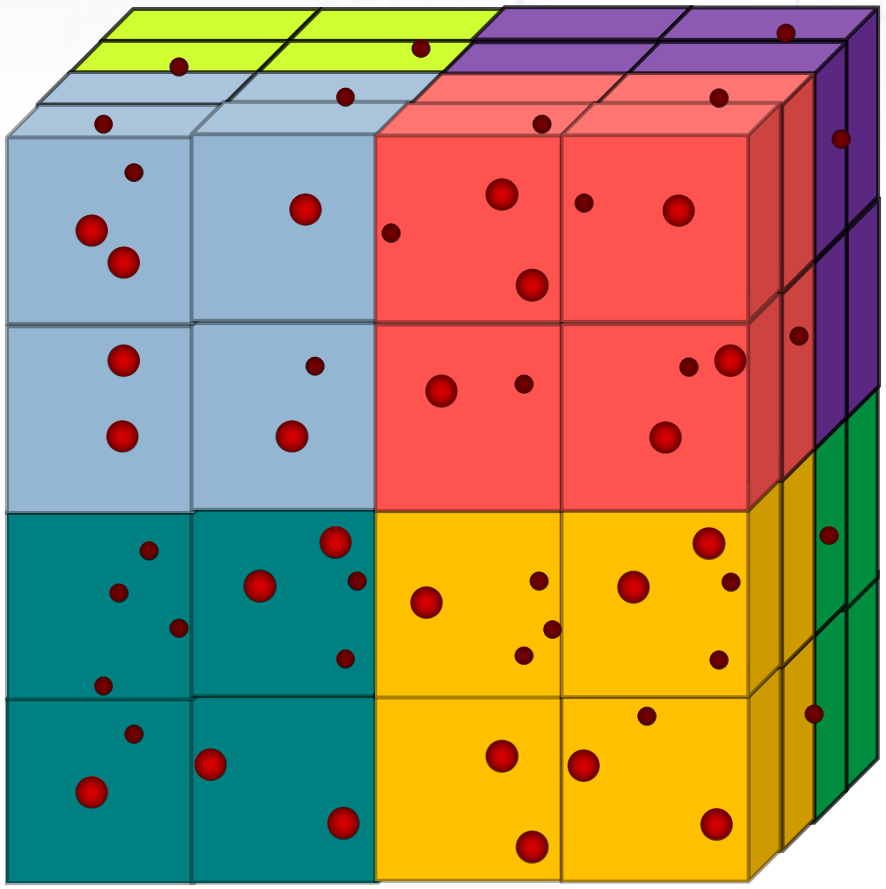

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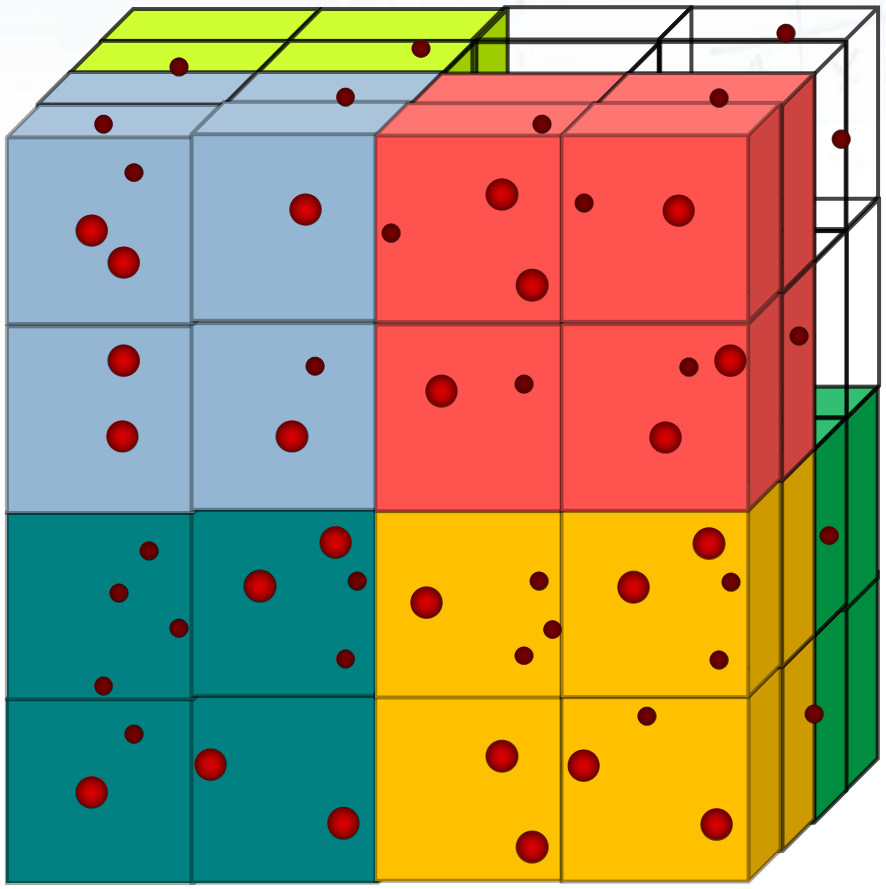

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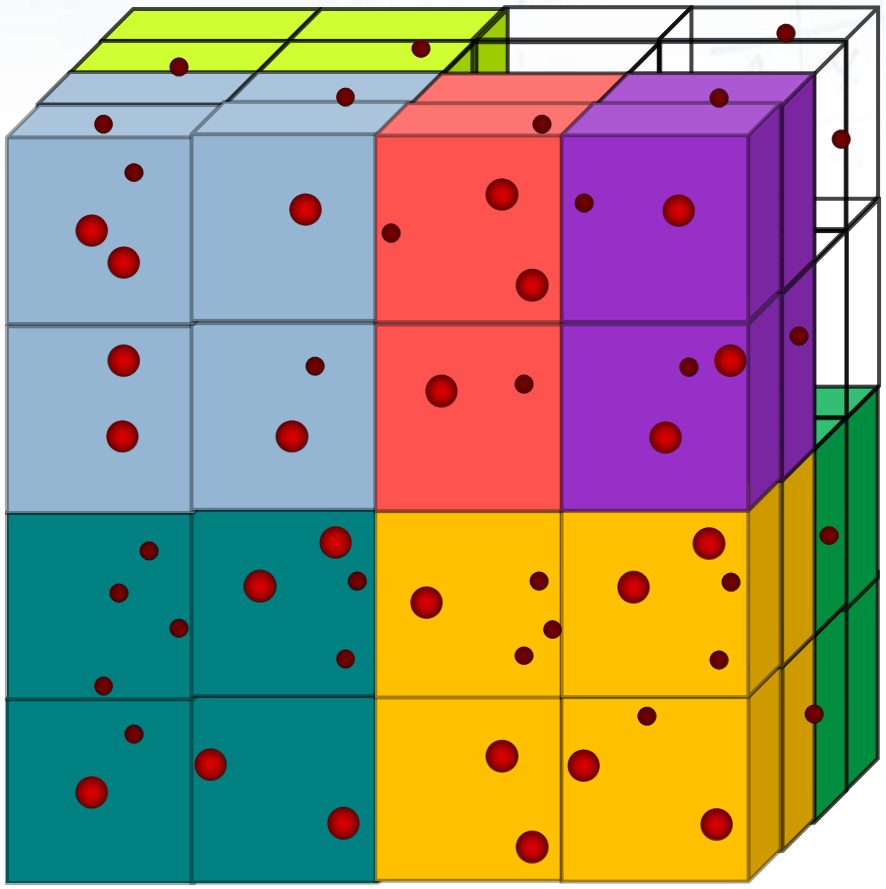

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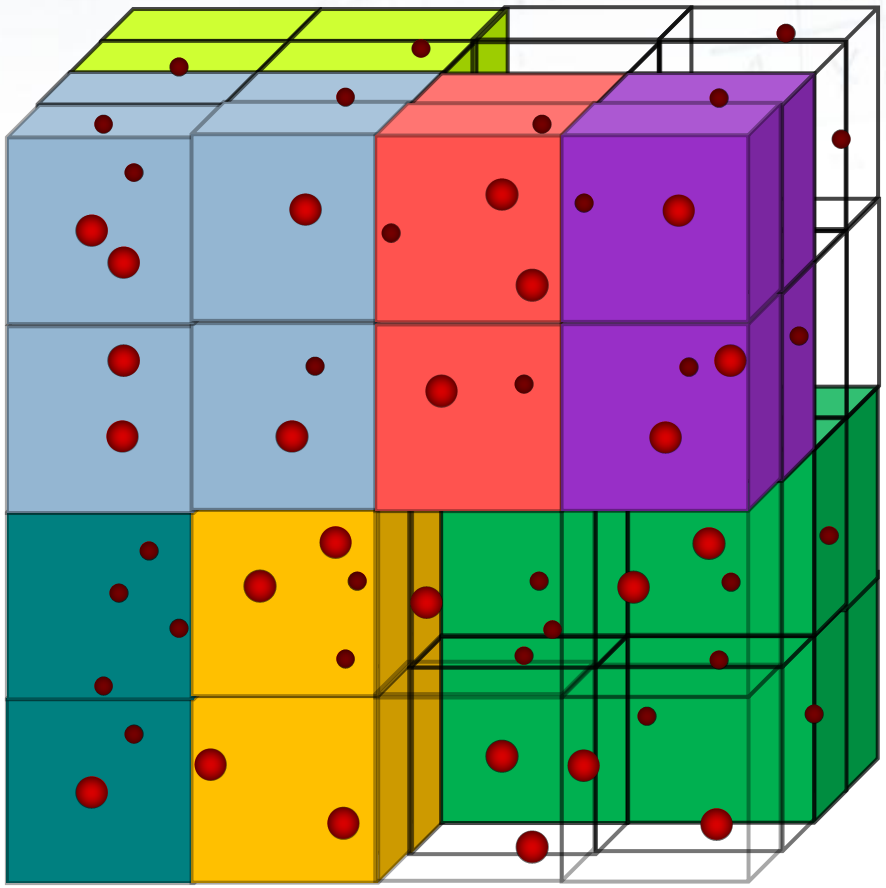

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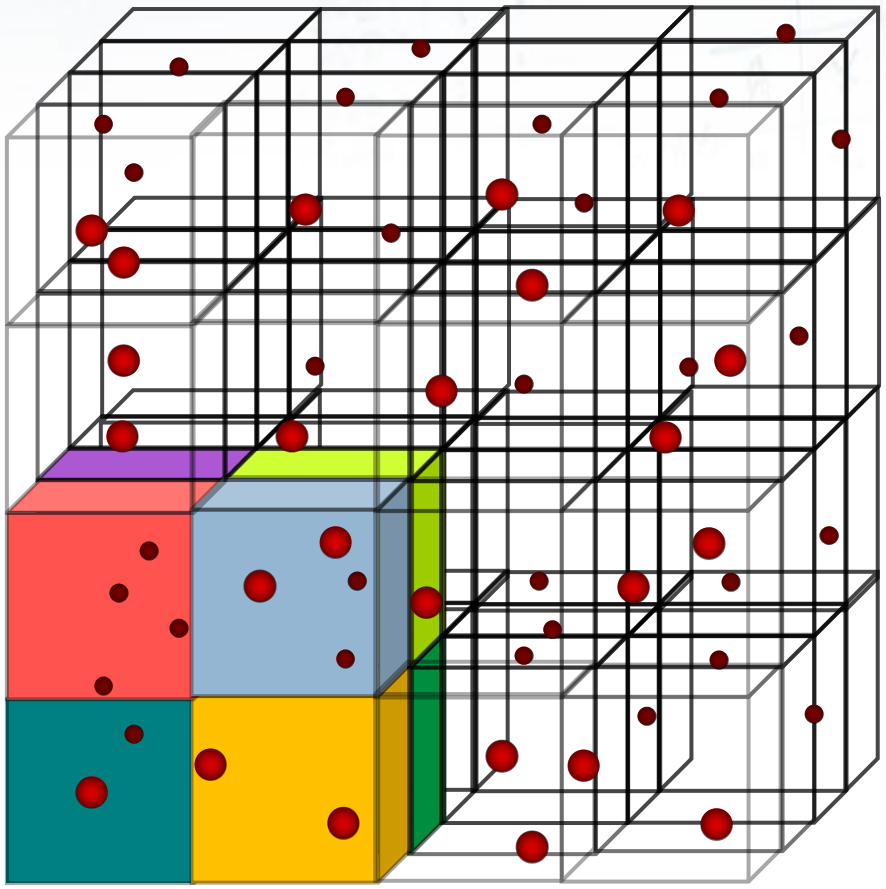

FluidAnimate

```
void computeForces(cell_t [][][] cells, dimentions_t d) {
   range_t range= { .x_start=0, .x_curr=0, .x_end=d.x_len, ...};
   do {
      par fluidAnimate (computeForces, cells, range);
   } finish;
}
par_task fluidAnimate {
  task computeForces(cell_t cell) {
    for (particle in cell) {
        struct cell_t [] ncells = getNeighbours(cell);
        particle.force = calcForce(particle, ncells);
  }}
  range_t [] subdivide(range_t curr_cells, int num) {
     // subdivide curr into num equal cubes, and add to new
  }
  cell_t getNext(cells_t [][][] cells, range_t range) {
     // return next cell in cells, or NULL if finished
}}
```

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FluidAnimate

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par_task fluidAnimate {
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}}
```

Microsoft Research

FluidAnimate

```
TASK(computeForces, fluidAnimate, range_t, cells_t [][][], cell_t cell, ({
    for (particle in cell) {
        struct cell_t [] ncells = getNeighbours(cell);
        particle.force = calcForce(particle, ncells);
    }
}));
SUBDIVIDE(fluidAnimate, range_t, ({
     // subdivide curr into num equal cubes, and add to new
}));
GETNEXT(fluidAnimate, cell_t [][][], cells_t, range_t, ({
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}));
```

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FluidAnimate

Par-task Type

Task Name

Task Args

```
TASK(computeForces, fluidAnimate, range_t, cells_t [][][], cell_t cell, ({
    for (particle in cell) {
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Microsoft Research

FluidAnimate

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FluidAnimate

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    for (particle in cell) {
        struct cell_t [] ncells = getNeighbours(cell);
        particle.force = calcForce(particle, ncells);
    }
}));
range_t[] __fluidAnimate_subdivide(range_t curr_cells, int num) {
     // subdivide curr into num equal cubes, and add to new
}
GETNEXT(fluidAnimate, cells_t, range_t, cell_t [][][], ({
     // return next cell in cells, or NULL if finished
}));
```

Microsoft Research

FluidAnimate

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Microsoft Research

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}));
range_t [] __fluidAnimate_subdivide(range_t curr_cells, int num) {
     // subdivide range into num equal cubes, and return new
}
cell_t __fluidAnimate_getNext(cells_t [][][] cells, range_t range) {
     // return next cell in range, or NULL if finished
}
```

```
void __computeForces_task(range_t my_range, cells_t [][][] cells) {
  cell_t cell = __fluidAnimate_getNext(cells, my_range);
  do {
    for (particle in cell) {
        struct cell_t [] ncells = getNeighbours(cell);
        particle.force = calcForce(particle, ncells);
    }
    if ((int num = calico_should_subdivide()) > 0) {
      range_t [] new_ranges = __fluidAnimate_subdivide(my_range, num);
      calico_schedule_par(__computeForces_task, new_ranges, cells);
       return;
  } while ((cell = __fluidAnimate_getNext(cells, my_range)) != NULL);
}
```

FluidAnimate

```
void __computeForces_task(range_t my_range, cells_t [][][] cells) {
  cell_t cell = __fluidAnimate_getNext(cells, my_range);
  do {
    for (particle in cell) {
        struct cell_t [] ncells = g
        particle.force = calcForce(
    }
    if ((int num = calico_should_subdi
      range_t[] new_ranges = __fluidAn
      calico_schedule_par(__computeForces_task, new_ranges, cells);
      return;
```

Automatic Repartitioning when necessary

Aggregation of multiple task iterations

```
void computeForces(cell_t [][][]cells, dimentions_t d) {
   range_t range= { .x_start=0, .x_curr=0, .x_end=d.x_len, ...};
   do {
      par_fluidAnimate (computeForces, cells, range);
   } finish;
}

}
```

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FluidAnimate

```
par_task fluidAnimate {

  task moveParticles(cell_t cell)    {   ...   }
  task computeDensities(cell_t cell) {   ...   }
  task computeForces(cell_t cell)    {   ...   }
  task renderCell(cell_t cell)       {   ...   }

  range_t [] subdivide(range_t curr_cells, int num) {
     // subdivide curr into num equal cubes, and add to new
  }
  cell_t getNext(cells_t [][][] cells, range_t range) {
     // return next cell in cells, or NULL if finished
  }
  bool calcOnDifferentCore(cell_t cell, range_t range) {
     // return true if cell is not within range
}}
```

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FluidAnimate

```
par_task fluidAnimate {
  task moveParticles(cell_t cell)    {
    for (particle in cell) {
      cell_t new_cell = calculateParticlesCell(particle);
      if (new_cell == cell) continue;
      if (onDifferentCore(new_cell)) {
        lockAndUpdate(new_cell, particle);
      } else {
        updateNoLock(new_cell, particle);
  }}}
  ...
  bool calcOnDifferentCore(cell_t cell, range_t range) {
     // return true if cell is not within range
  }
  ...
}}
```

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  }}}
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  bool calcOnDifferentCore(cell_t cell, range_t range) {
     // return true if cell is not within range
  }
  ...
}}
```

```
calcOnDifferentCore(new_cell, my_range);
```

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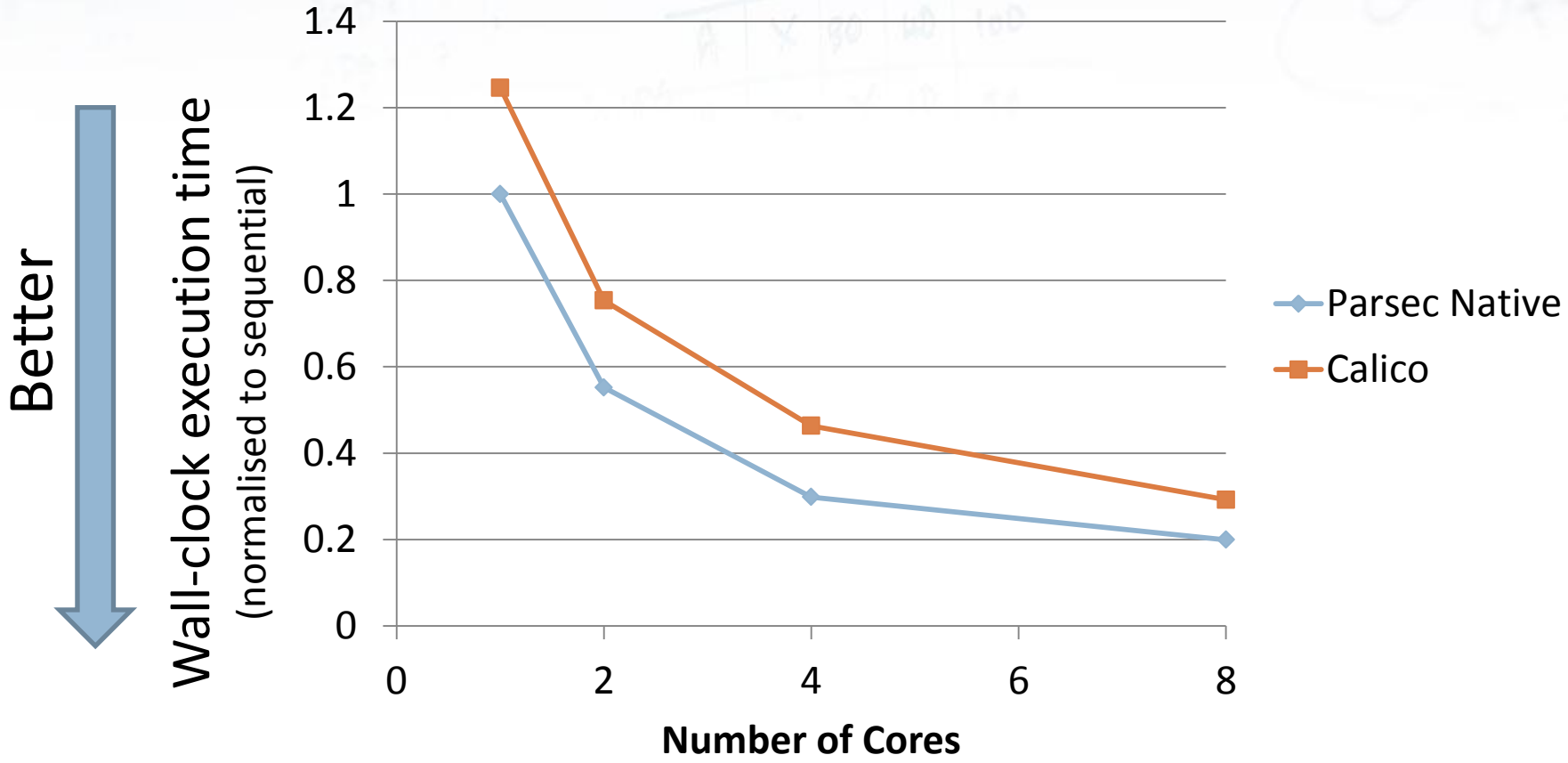
FluidAnimate Results

- No competition for CPU-time



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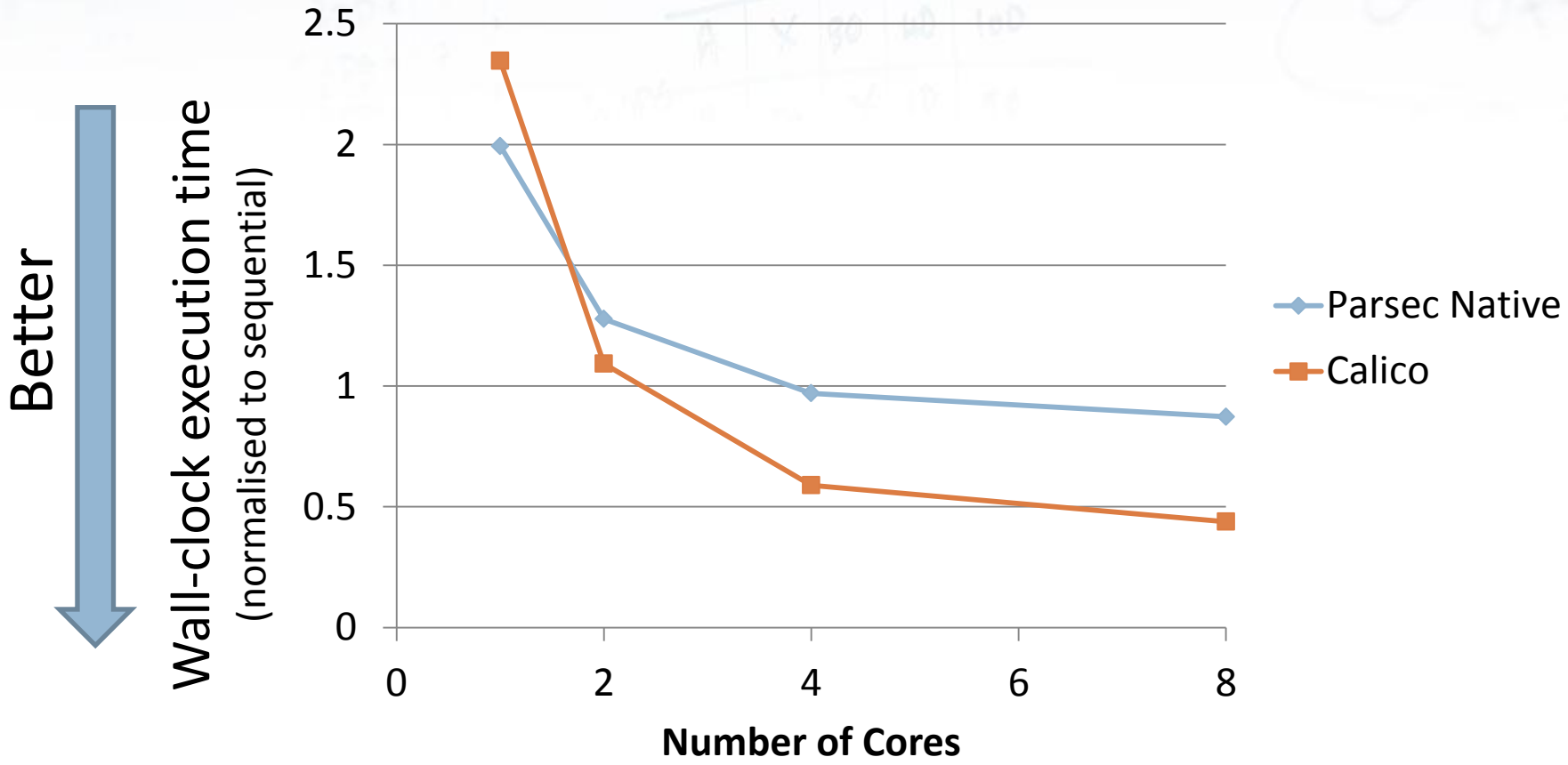
FluidAnimate Results

- Competition for CPU-time



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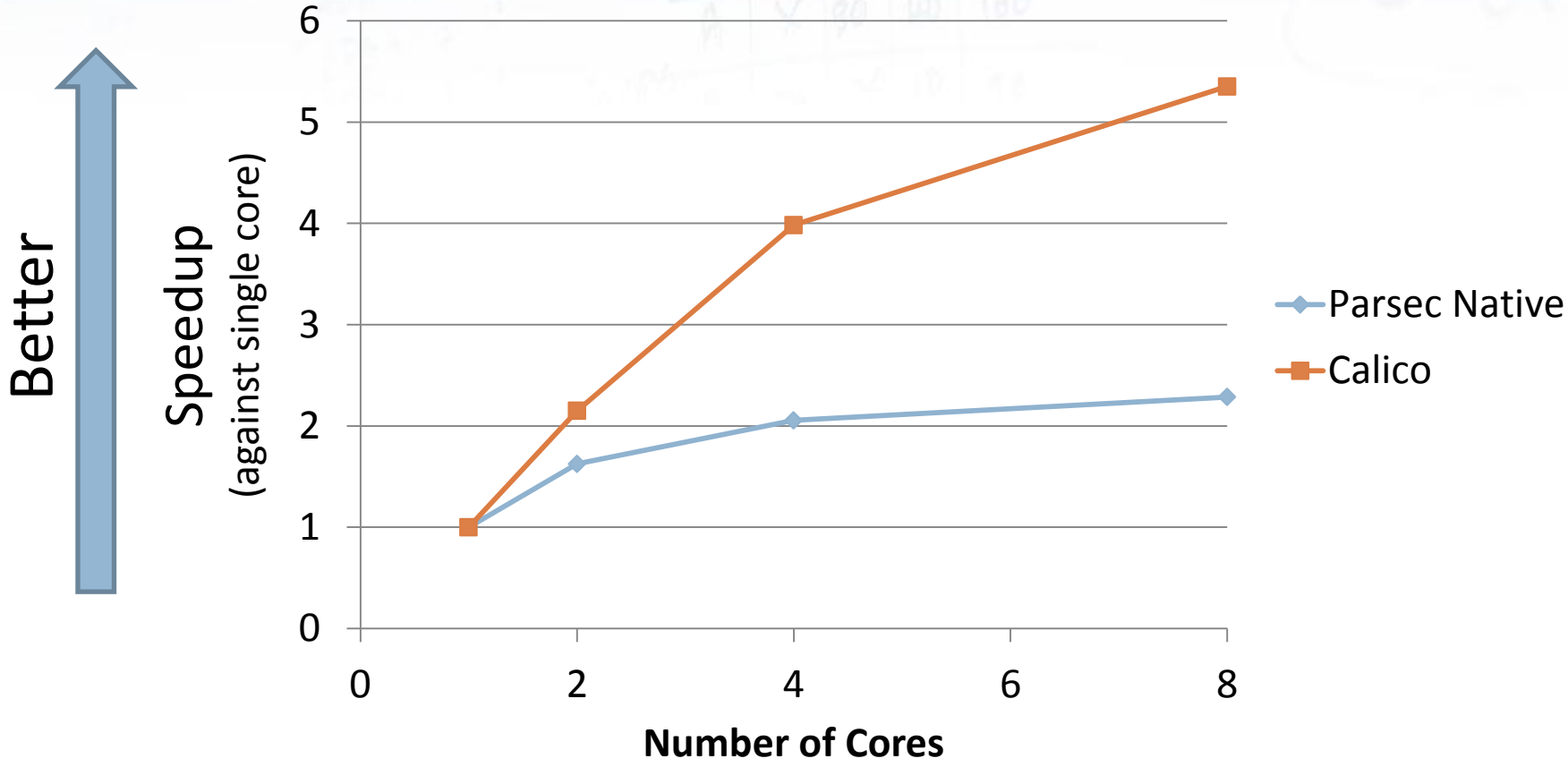
FluidAnimate Results

- Competition for CPU-time



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Status

- Supported Benchmarks:
  - Blacksholes
  - FluidAnimate
  - Dedup
  - Delaunay Triangulation (work ongoing)
- Supported on non-cache-coherent hardware
  - Blacksholes
  - FluidAnimate

Future Directions

- OS / Runtime System co-design
  - Blur the OS / Runtime boundary with Calico / Barrelfish
  - Inform the OS of changes in resource demands
  - Inform the runtime of changing core-counts / competing applications
  - Provide architecture details (e.g., cache layout) to runtime
  - Have runtime automatically adapt application behaviour using this information

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turning ideas into reality.

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