TECHNISCHE UNIVERSITÄT DRESDEN

“PARTITIONING” IN MPI
FAULT TOLERANCE FOR MPI
COMMUNICATION AND NOISE AS HPC BOTTLENECK
DYNAMIC LOAD BALANCING

DISTRIBUTED OPERATING SYSTEMS, SCALABILITY, SS 2019

(THANKS TO AMNON BARAK, CARSTEN, MAKSYM, ALEX MARGOLIN, ...)

Hermann Härtig, SS 2019

THIS LECTURE

- Partitioning:
  bulk synchronous execution
  MPI collectives, Fault Handling
- Communication and Noise
- Load Balancing (MosiX):
  migration mechanisms
  information dissemination
  decision making

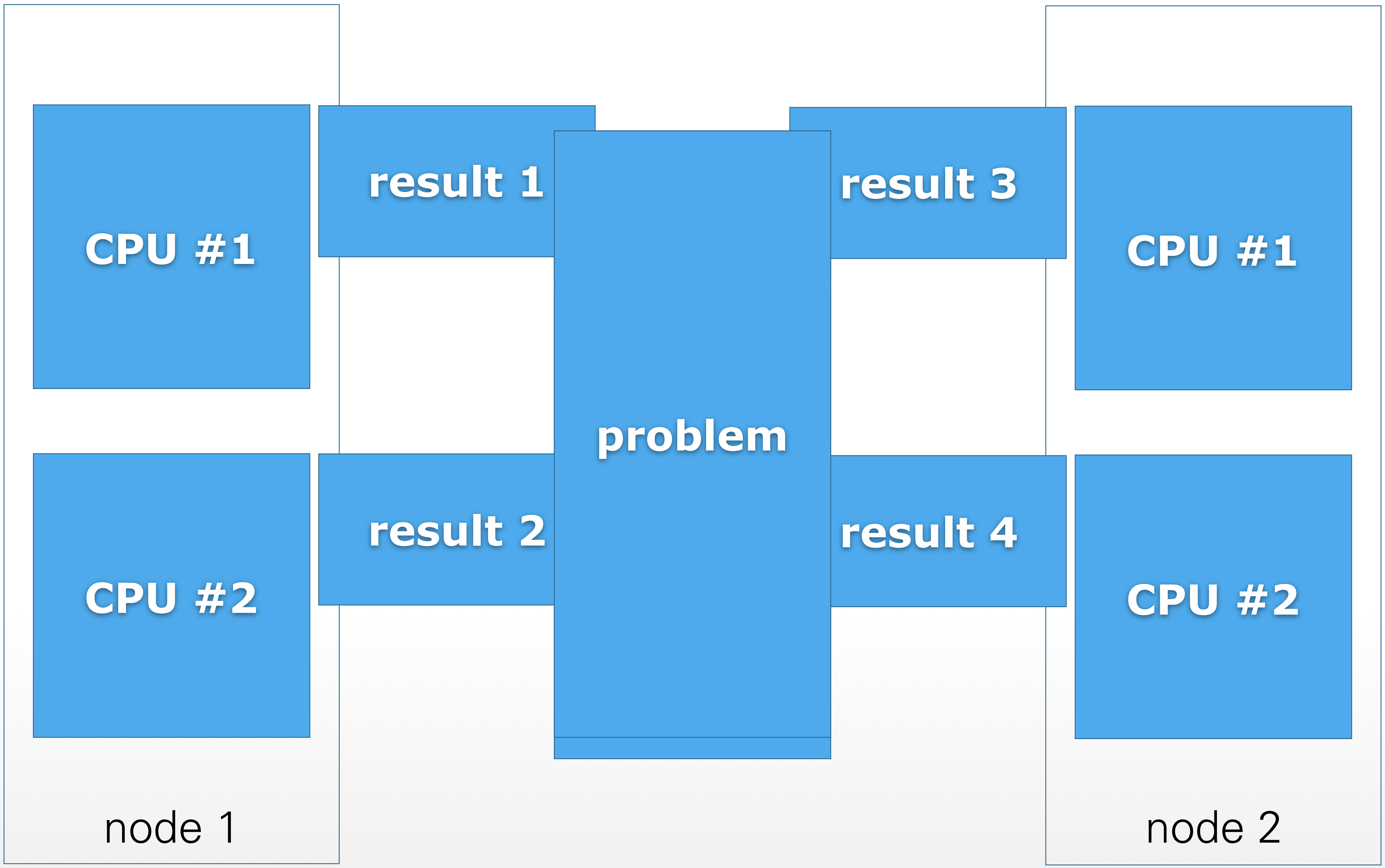
STARTING POINTS

- independent OS processes
- bulk synchronous execution (HPC)
  - sequence: compute - communicate
  - all processes wait for (all) other processes
  - often: message passing
    for example Message Passing Library (MPI)

BULK SYNCHRONOUS

- all processes execute same program
- while (true)
  { work; exchange data (collective operation)}
- common in
  High Performance Computing:
  Message Passing Interface (MPI)
  library

DIVIDE AND CONQUER



BRIEF INTRO INTO "MPI"

MPI: Message Passing Interface

- Library for message-oriented parallel programming
- Common usage but not mandatory
  Bulk Synchronous Programming model:
  - Multiple instances of same program
  - Independent calculation
  - Communication, synchronization

MPI STARTUP & TEARDOWN

- MPI program is started on all processors
- `MPI_Init()`, `MPI_Finalize()`
- Communicators (e.g., MPI_COMM_WORLD)
  - `MPI_Comm_size()`
  - `MPI_Comm_rank()`:
    "Rank" of process within this set
  - Typed messages
- (Dynamically create and spread processes using `MPI_Spawn()` (since MPI-2))

MPI EXECUTION

- Communication

- Synchronization

MPI EXECUTION

- Communication
  - Point-to-point
- Synchronization

```
MPI_Send(
   void* buf,
   int count,
   MPI_Datatype,
   int dest,
   int tag,
   MPI_Comm comm
)
MPI_Recv(
   void* buf,
   int count,
   MPI_Datatype,
   int source,
   int tag,
   MPI_Comm comm,
   MPI_Status *status
)
```

MPI EXECUTION

- Communication
  - Point-to-point
  - Collectives
- Synchronization

```
MPI_Bcast(
   void* buffer,
   int count,
   MPI_Datatype,
   int root,
   MPI_Comm comm
)
MPI_Reduce(
   void* sendbuf,
   void *recvbuf,
   int count
   MPI_Datatype,
   MPI_Op op,
   int root,
   MPI_Comm comm
)
```

MPI EXECUTION

- Communication
  - Point-to-point
  - Collectives
- Synchronization
  - Test
  - Wait

```
MPI_Test(
   MPI_Request* request,
   int *flag,
   MPI_Status *status
)
```

```
MPI_Wait(
   MPI_Request* request,
   MPI_Status *status
)
```

MPI EXECUTION

- Communication
  - Point-to-point
  - Collectives
- Synchronization
  - Test
  - Wait
  - Barrier

```
MPI_Barrier(
 MPI_Comm comm
)
```

MPI EXECUTION

- Communication
  - Point-to-point
  - Collectives
- Synchronization
  - Test
  - Wait
  - Barrier

BLOCK AND SYNC

	blocking call	non-blocking call
synchronous communication	returns when message has been delivered (i.e. received by some)	returns immediately, sender later checks for delivery (Test/Wait)
asynchronous communication	returns when send buffer can be reused	returns immediately, sender later checks for send buffer

"buffer": variable containing the message to be sent

CODE SKELETON

```
int rank, total;
MPI_Init();
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &total);

MPI_Bcast(...);
/* work on own part, determined by rank */

if (rank == 0) {
  for (int rr = 1; rr < total; ++rr)
    MPI_Recv(...);
  /* Generate final result */
} else {
    MPI_Send(...);
}
MPI_Finalize();
```

AMDAHLS' LAW

for parallel systems:

- P: section that can be parallelized
- 1-P: serial section
- N: number of CPUs

$$\text{Speedup}(P,N) = \frac{1}{\left(1 - P + \frac{P}{N}\right)}$$

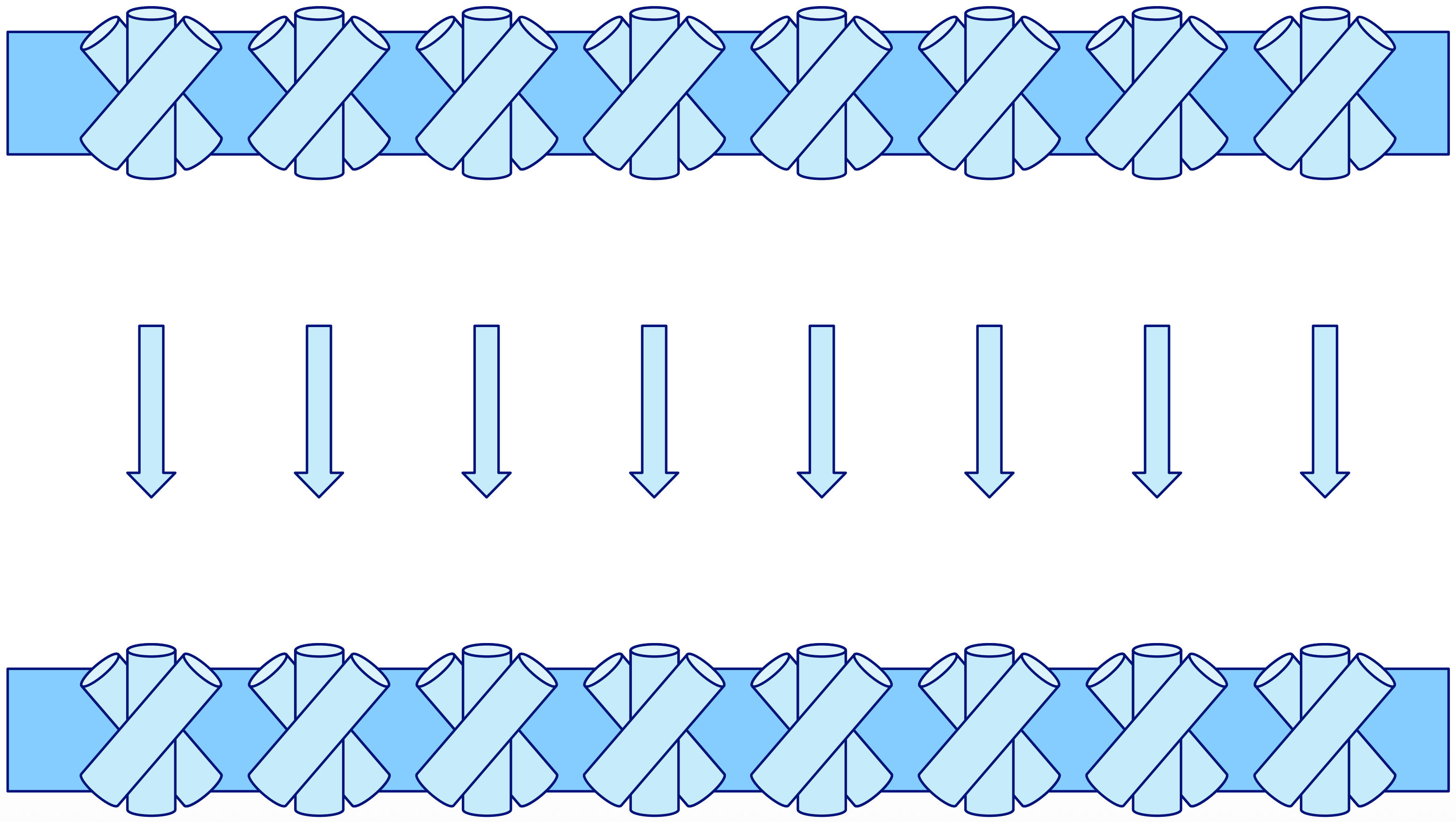
AMDAHL'S LAW

Serial section:

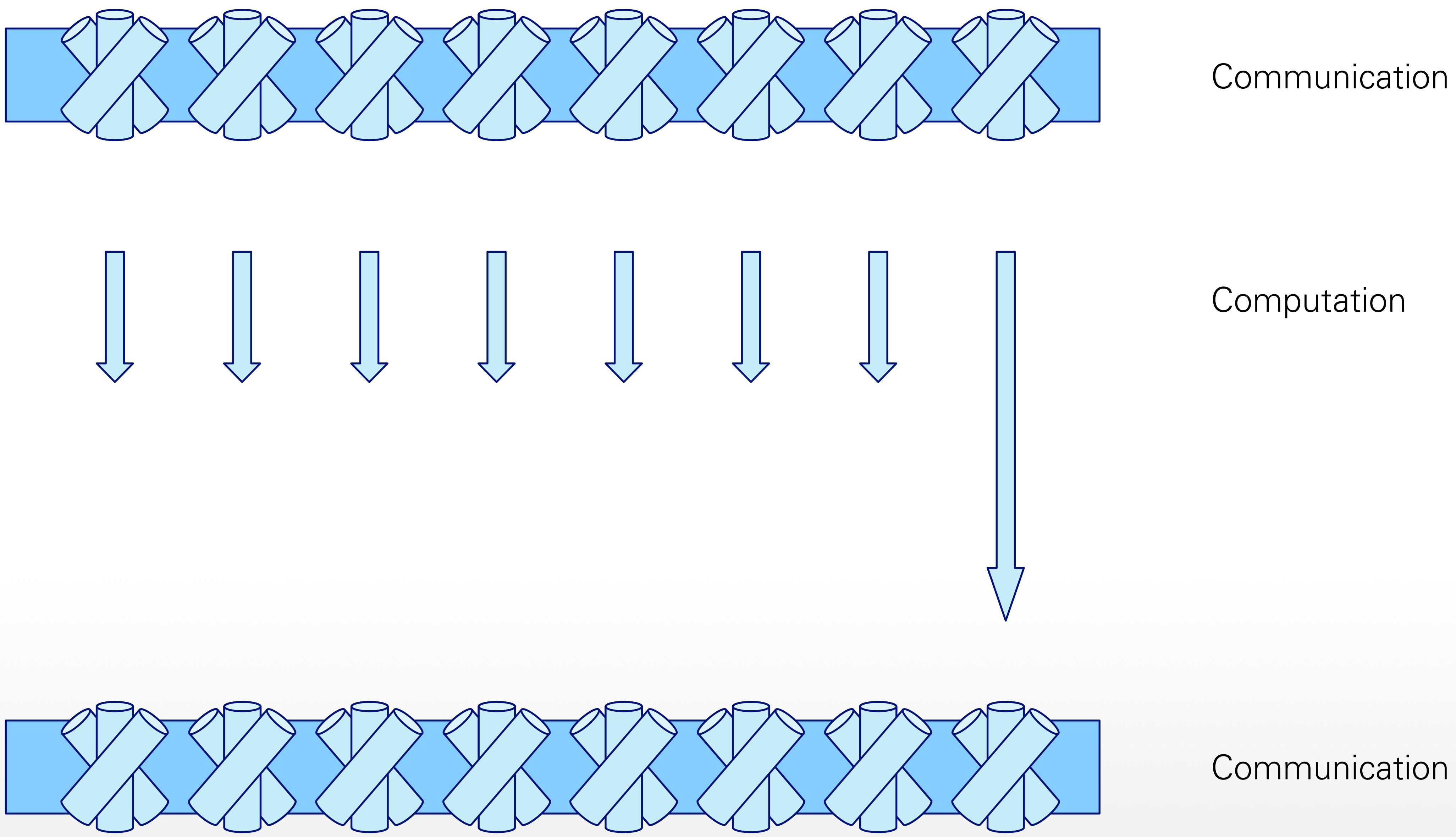
communication op, longest sequential section

	Parallel,	"Serial",	possible speedup:	
▪	1ms,	100 µs:	1/0.1	→ 10
▪	1ms,	1 µs:	1/0.001	→ 1000
▪	10 µs,	1 µs:	0.01/0.001	→ 10
▪	…			

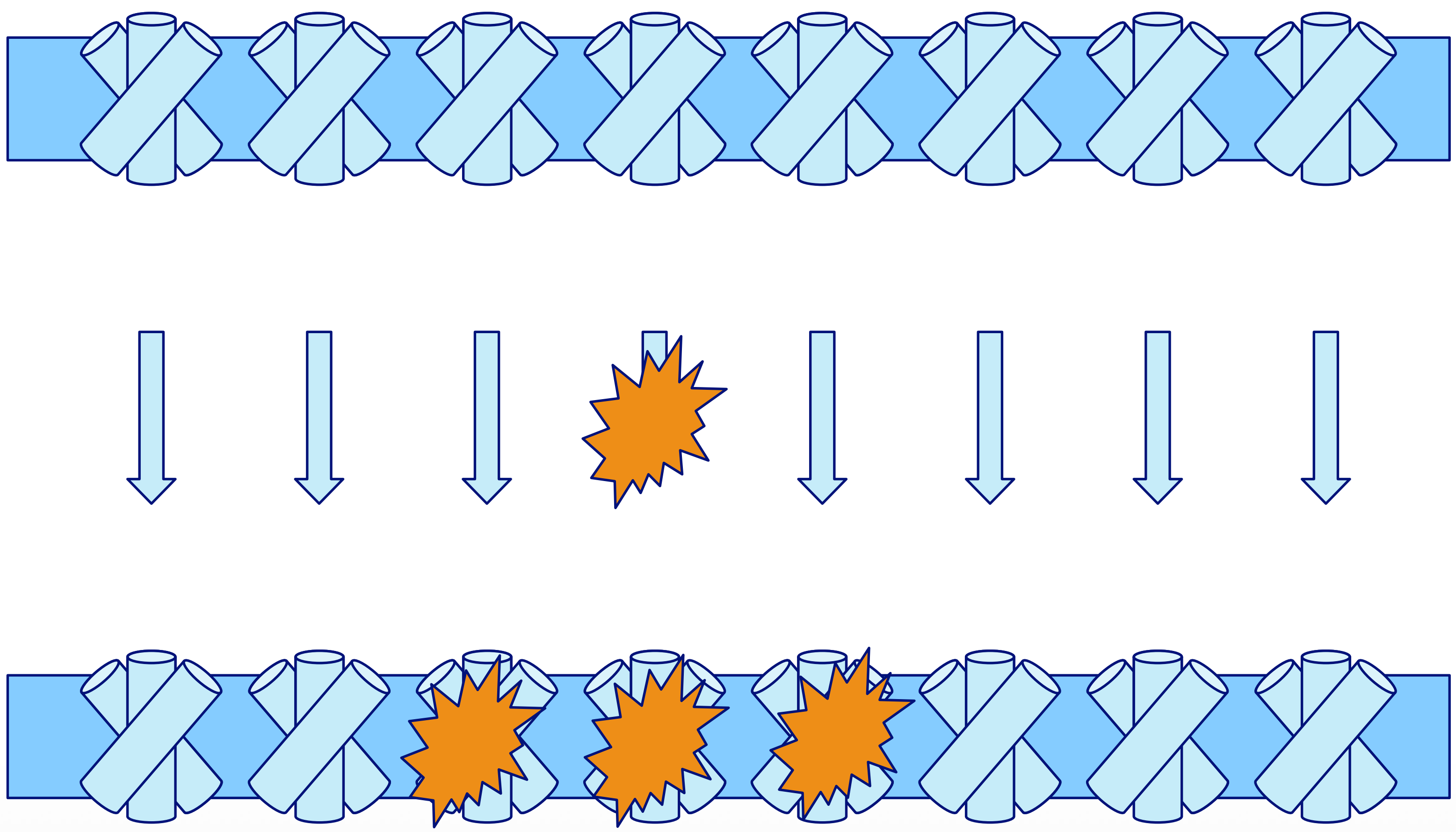
BLOCK SYNCHRONOUS EXECUTION



BLOCK SYNCHRONOUS EXECUTION



BLOCK SYNCHRONOUS EXECUTION



Communication

Computation

Communication

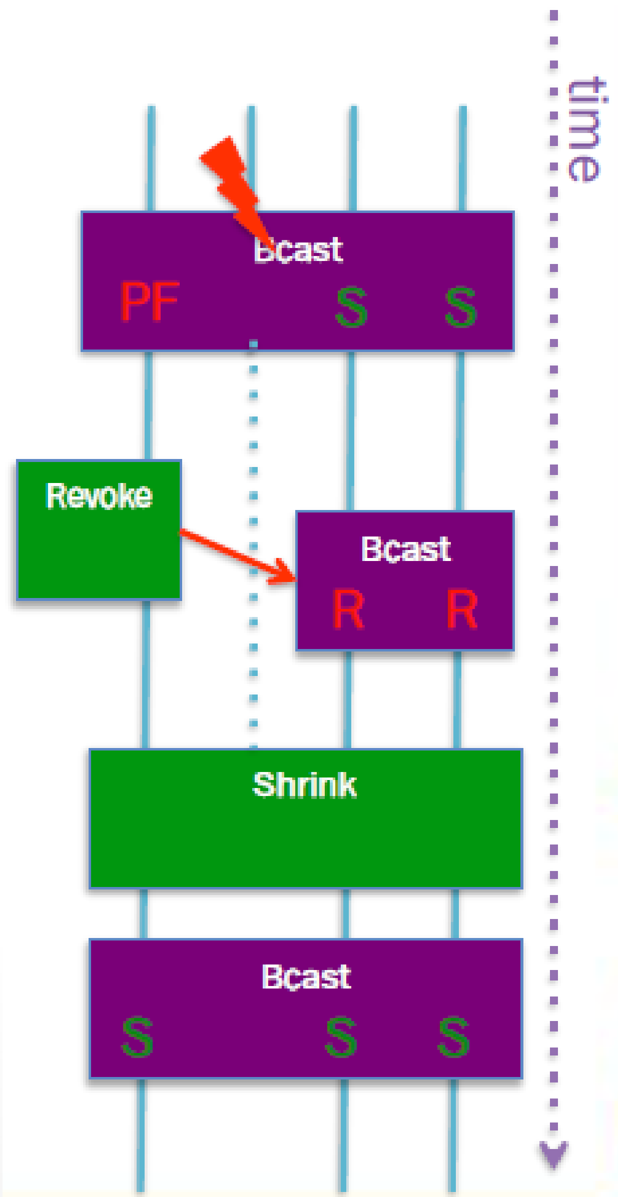
ITERATIVE ALGORITHM WITH CHECKPOINT

```
. . .

for(int t = 0; t < TIMESTEPS; t++) {
   /* ... Do work ... */

   SCR_Need_checkpoint(&flag);
   if (flag) {
     SCR_Start_checkpoint();
     SCR_Route_file(file, scr_file);
     /* save checkpoint into scr_file */
     SCR_Complete_checkpoint(1);
   }
 }
. . .
```

RECOVER

```
MPI_Init();
SCR_Init();


if (SCR_Route_file(name, ckpt_file) ==
SCR_SUCCESS) {
 // Read checkpoint from ckpt_file
} else {
 // There is no existing checkpoint
 // Normal program startup
}
```

ULFM USER LEVEL FAULT MITIGATION



Notification

- MPI_Comm_failure_ack(comm)
  - Resumes matching for MPI_ANY_SOURCE
- MPI_Comm_failure_get_acked(comm, &group)
  - Returns to the user the group of processes acknowledged to have failed

Propagation

- MPI_Comm_revoke(comm)
  – Non-collective collective, interrupts all operations on comm (future or active, at all ranks) by raising MPI_ERR_REVOKED

Recovery

- MPI_Comm_shrink(comm, &newcomm)
  – Collective, creates a new communicator without failed processes (identical at all ranks)
- MPI_Comm_agree(comm, &mask)
  – Collective, agrees on the AND value on binary mask, ignoring failed processes (reliable AllReduce), and the return core

GENERAL DEFINITION: SCALABILITY

Scalability:

Scalability is the property of a system to handle a growing amount of work by adding resources to the system.

Wikipedia (2019) and many other sources

SCALABILITY: WEAK ./. STRONG

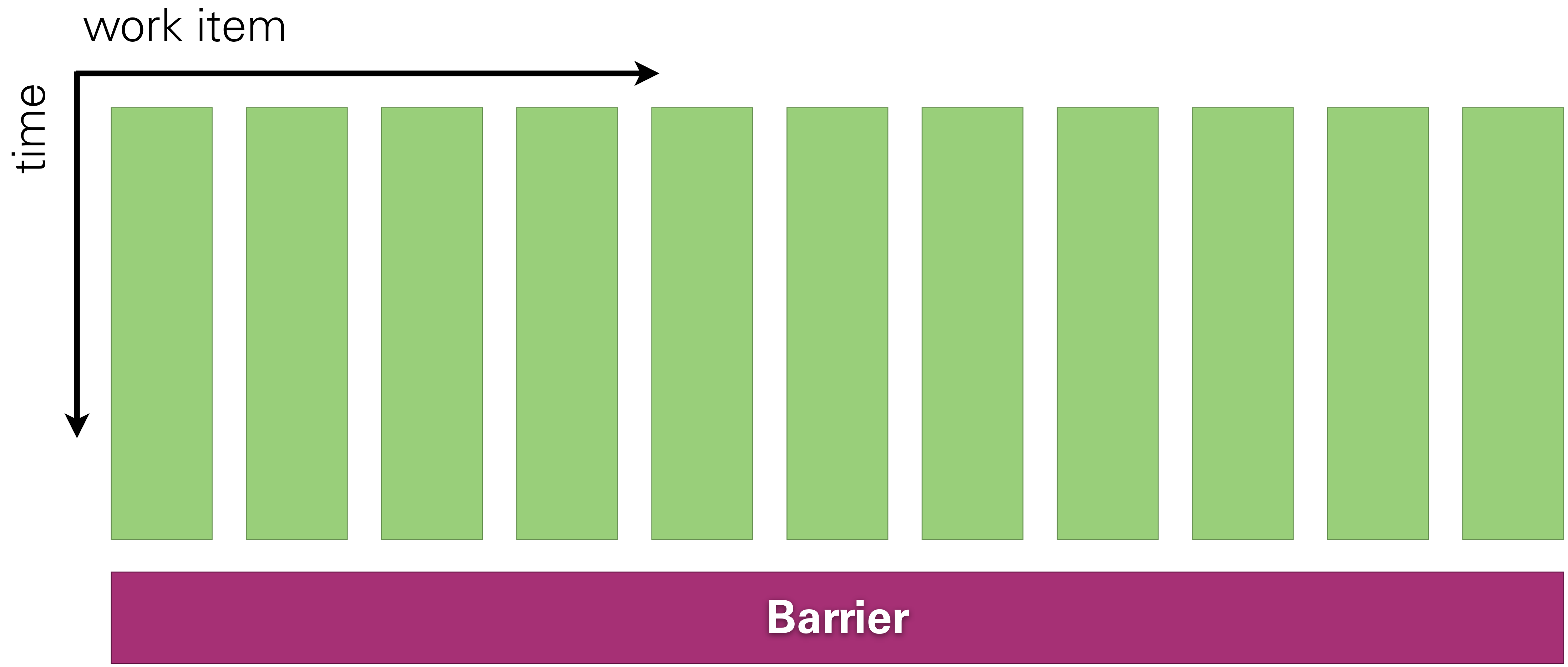
ability of a system to use growing resources

- weak:
  to handle growing load, larger problem,
- strong:
  accelerate existing work load, same problem

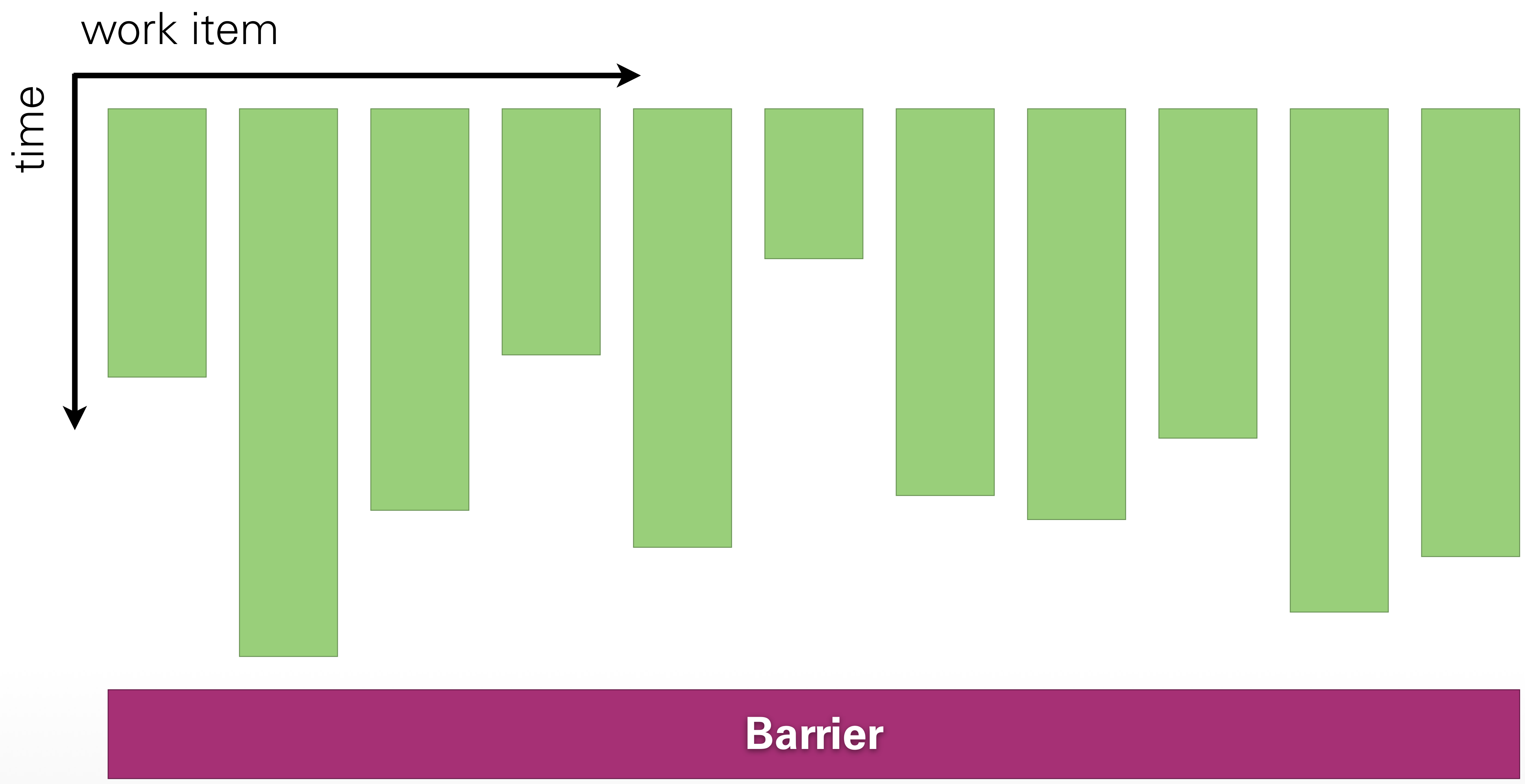
PROBLEMS

- noise
  - execution time jitter
  - interrupt latency
- balance load in case of unbalanced applications

THE NEED FOR BALANCING



THE NEED FOR BALANCING



OPERATING SYSTEM "NOISE"

Use common sense to avoid:

- OS usually not directly on the critical path,
  BUT OS controls: interference via interrupts, caches, network, memory bus, (RTS techniques)
- avoid or encapsulate side activities
- small critical sections (if any)
- partition networks to isolate traffic of different applications (HW: Blue Gene)
- do not run Python scripts or printer daemons in parallel

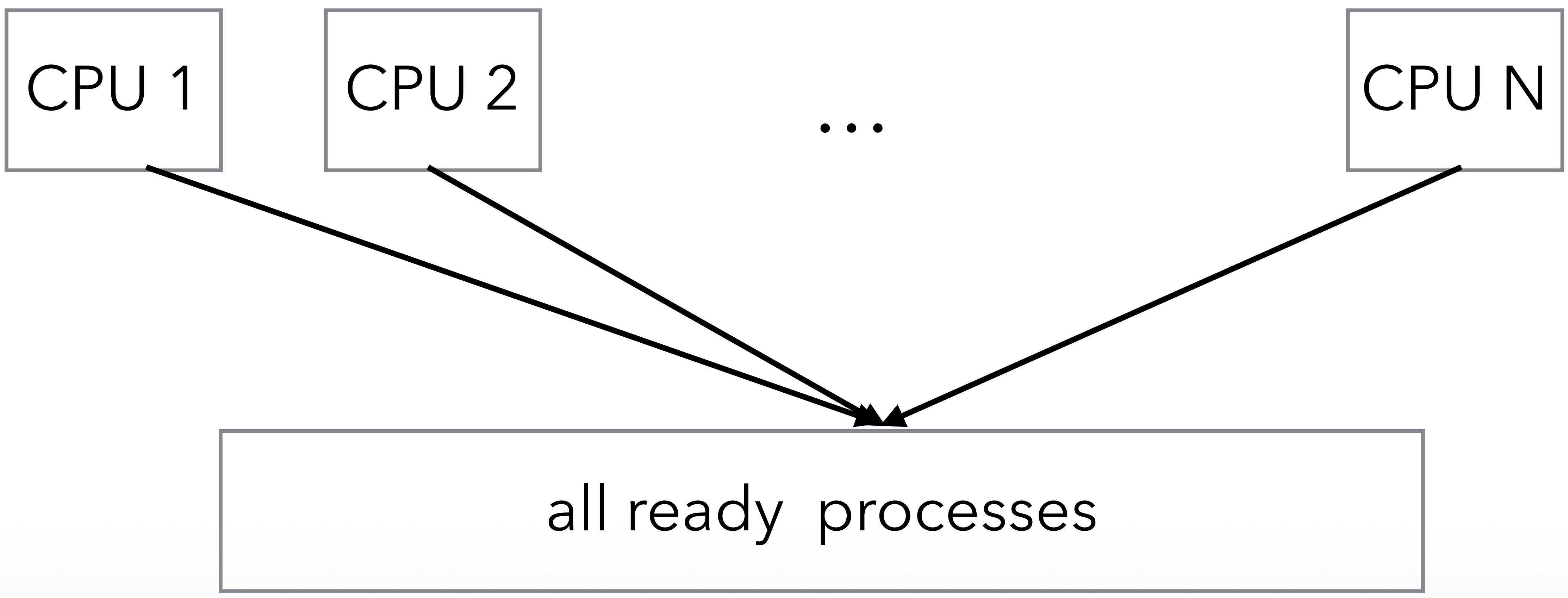
RESEARCH TOPIC

- use small kernel to isolate

balancing in systems architecture

- application
- run-time library
- operating system

SCHEDULER: GLOBAL RUN QUEUE



immediate approach: global run queue

SCHEDULER: GLOBAL RUN QUEUE

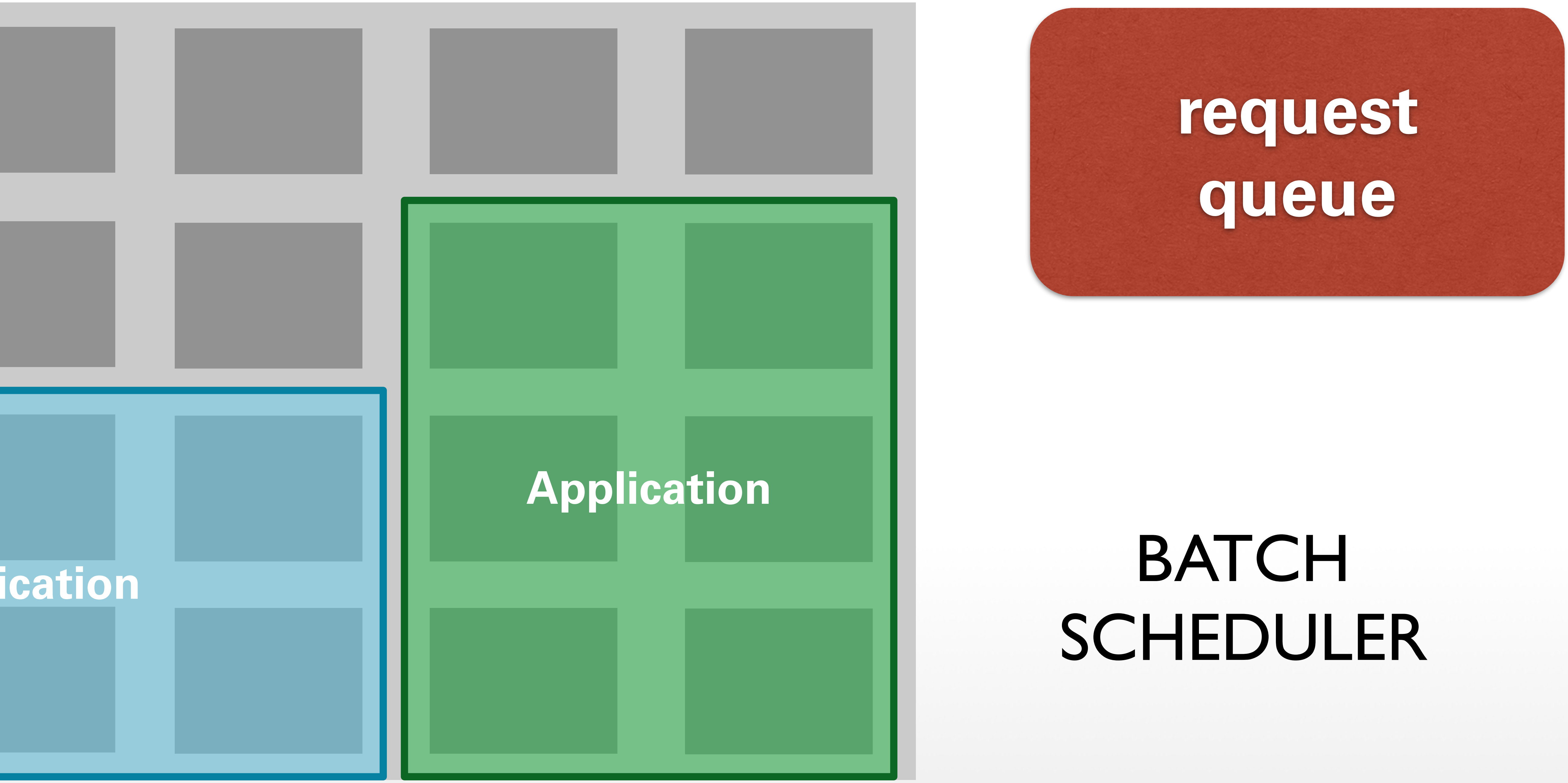
- … does not scale
  - shared memory only
  - contended critical section
  - cache affinity
  - …
- ⇨ separate run queues with explicit movement of processes

OS/HW & APPLICATION

High Performance Computing

- Operating System / Hardware:
  "All" participating CPUs: active / inactive
  - Partitioning (HW)
  - Gang Scheduling (OS)
- Within Gang/Partition:
  Applications balance !!!

HW PARTITIONS & ENTRY QUEUE

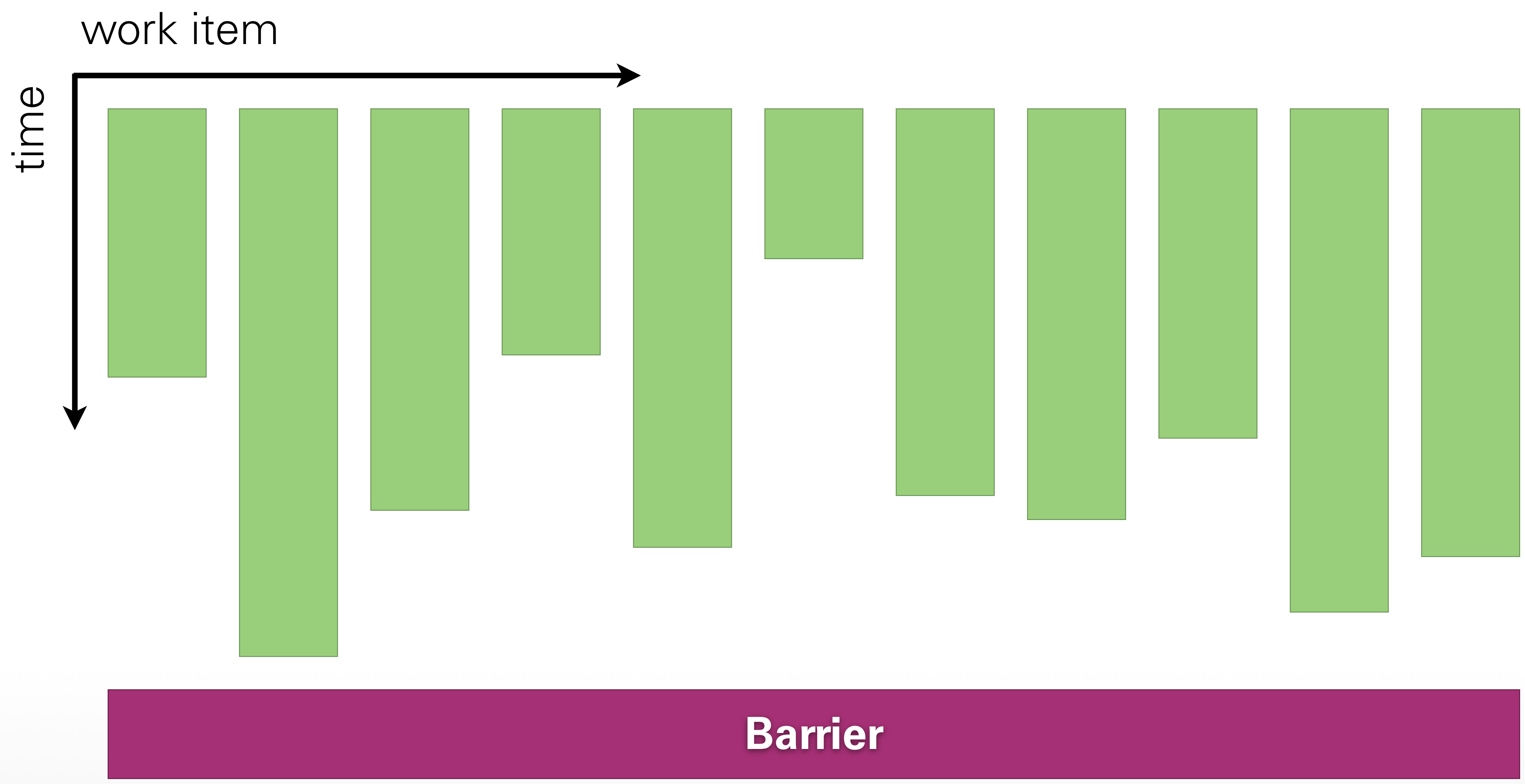


BATCH SCHEDULER

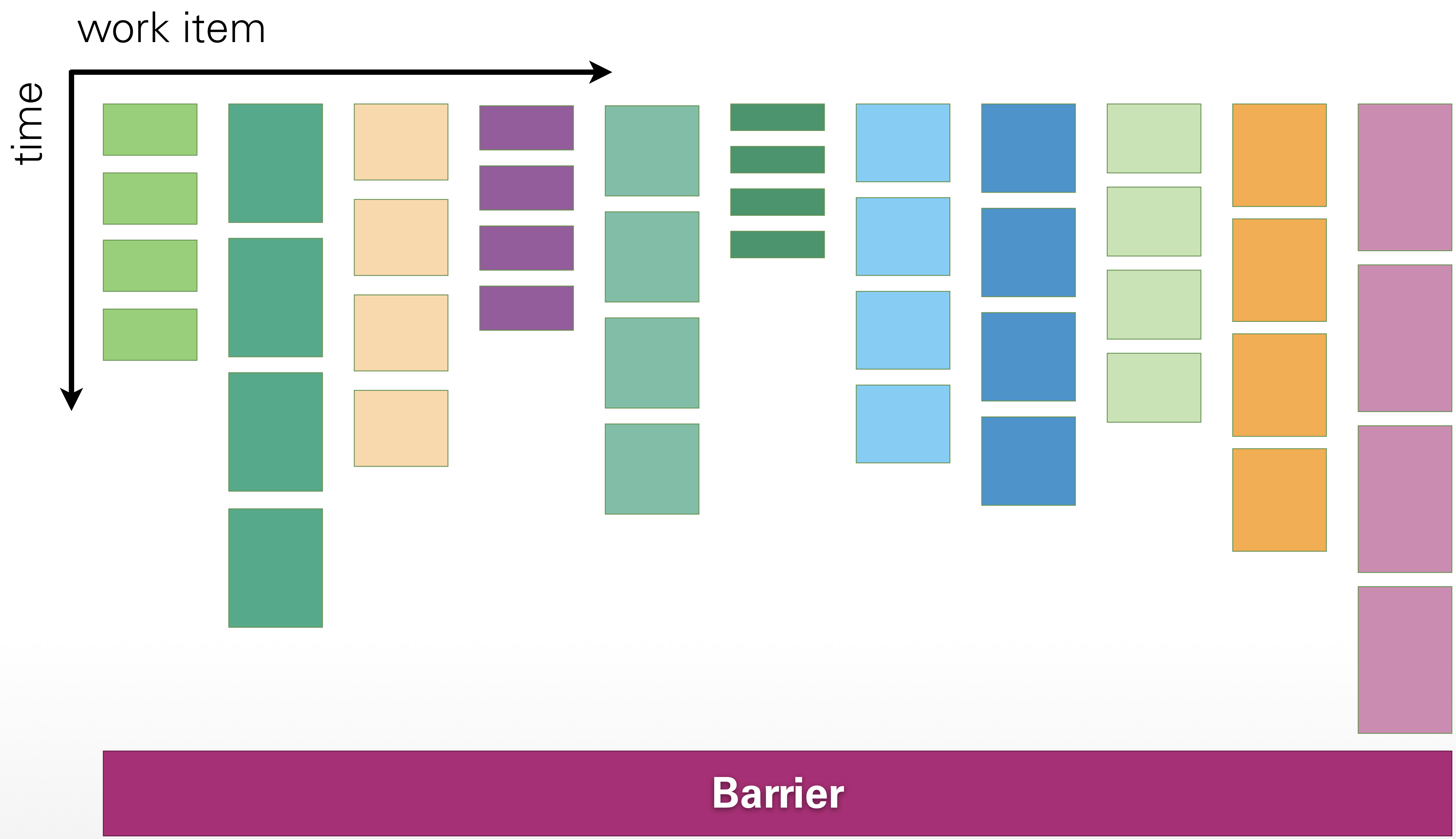
PROPERTIES HW PARTITIONS

- optimizes usage of network
- takes OS off critical path (busy waiting)
- best for strong scaling
- burdens application/library with balancing
- potentially wastes resources
- current state of the art in High Performance Computing (HPC)

TOWARDS SYSTEM-LEVEL BALANCING

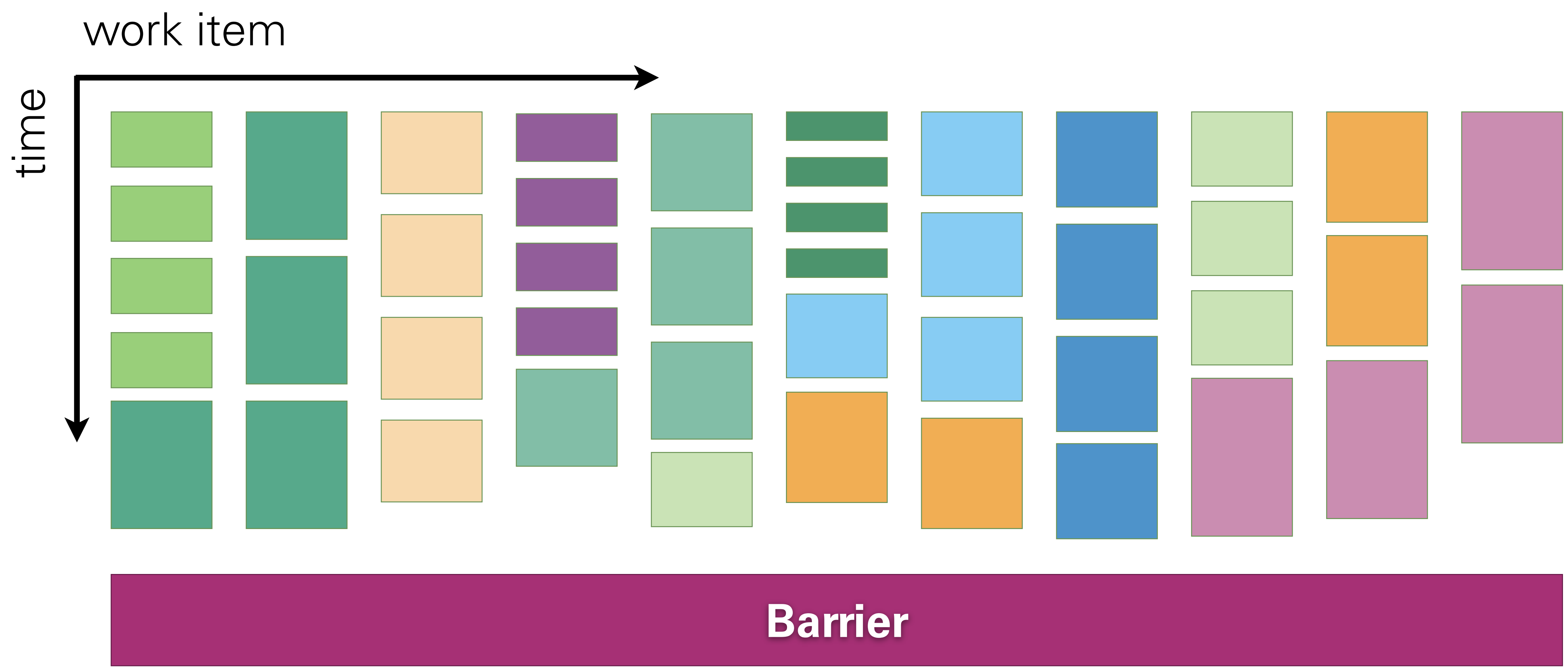


SPLITTING BIG JOBS



many more jobs than cores

SMALL JOBS (NO DEPS)



Execute small jobs in parallel (if possible)

BALANCING AT LIBRARY LEVEL

Programming Model

- many (small) decoupled work items
- overdecompose
  create more work items than active units
- run some balancing algorithm

Example: CHARM ++

BALANCING AT SYSTEM LEVEL

- create (many) more processes
- use OS information on run-time and system state to balance load
- examples:
  - run multiple applications
  - create more MPI processes than nodes (!)

CAVEATS

added overhead

- additional communication between smaller work items (memory & cycles)
- more context switches
- OS on critical path (for example communication)

BALANCING ALGORITHMS

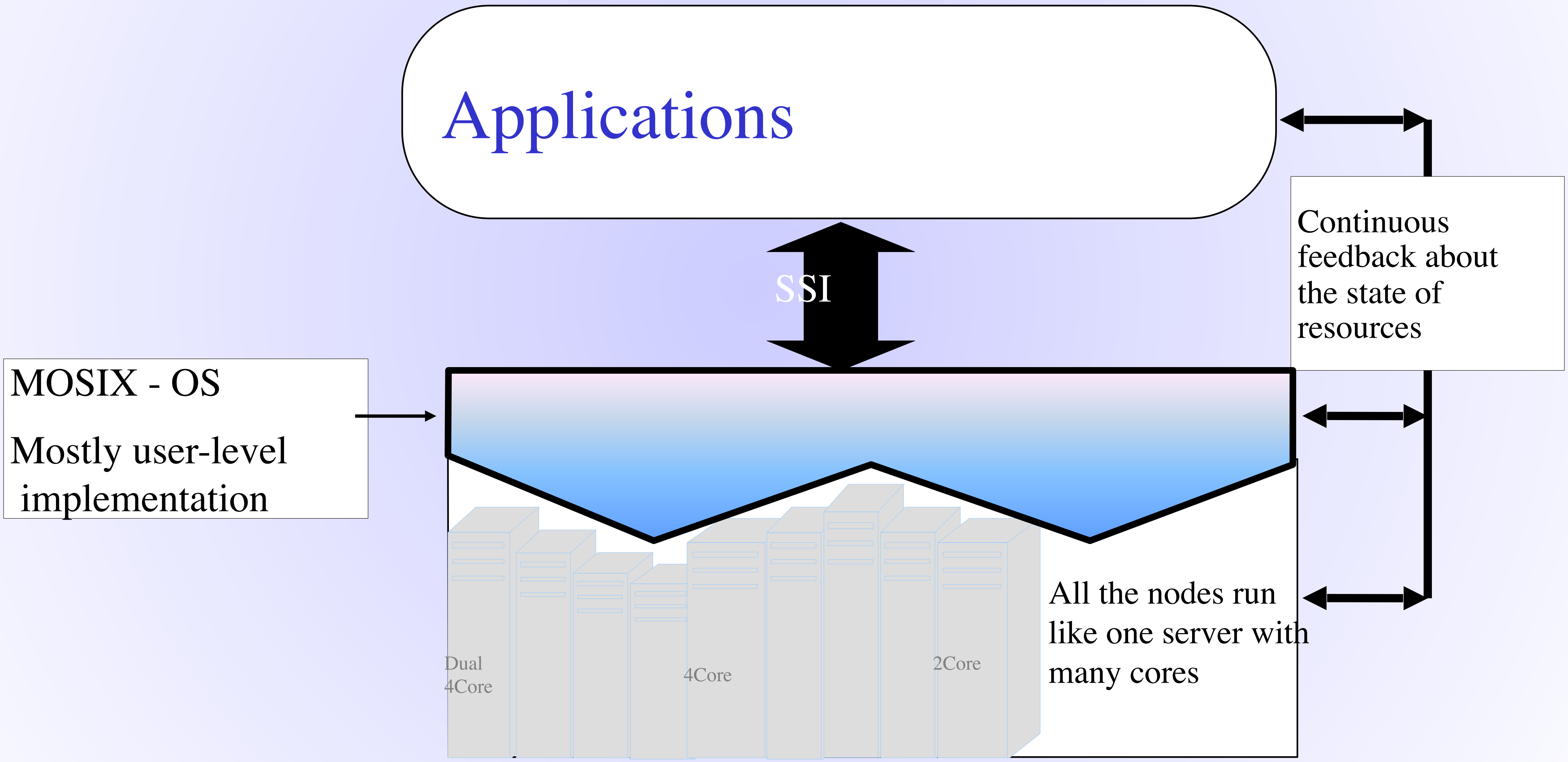
required:

- mechanism for migrating load
- information gathering
- decision algorithms

MosiX system as an example

-> Barak's slides now

MOSIX is a unifying management layer



Copyright © Amnon Barak 2011

The main software components

1. Preemptive process migration
   - Can migrate a running processes anytime
   - Like a course-grain context switch
     - Implication on caching, scheduling, resource utilization
2. OS virtualization layer
   - Allows a migrated process to run in remote nodes
3. On-line algorithms
   - Attempt to optimize a given goal function by process migration
     - Match between required and available resources
   - Information dissemination – based on partial knowledge

Note: features that are taken for granted in shared-memory systems, are not easy to support in a cluster

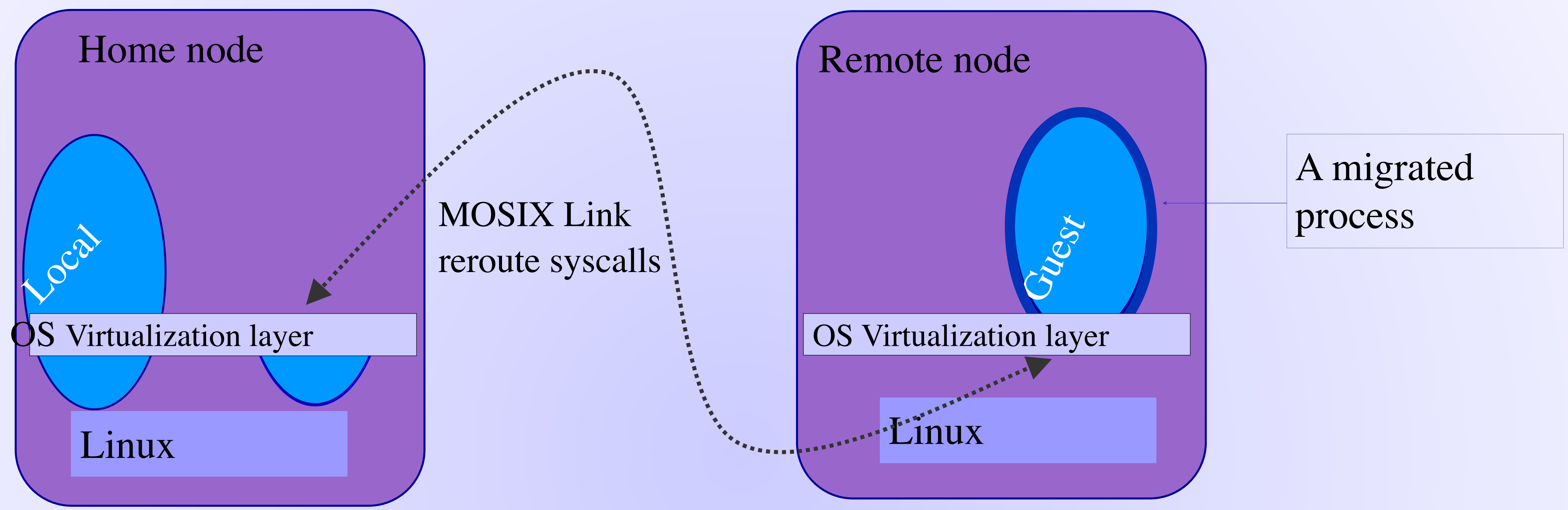
Copyright © Amnon Barak 2011

The OS virtualization layer

- A software layer that allows a migrated process to run in remote nodes, away from its home node
  - All system-calls are intercepted
    - Site independent sys-calls are performed locally, others are sent home
  - Migrated processes run in a sandbox
- Outcome:
  - A migrated process seems to be running in its home node
  - The cluster seems to the user as one computer
  - Run-time environment of processes are preserved - no need to change or link applications with any library, copy files or login to remote nodes
- Drawback: increased (reasonable) communication overhead

Copyright © Amnon Barak 2011

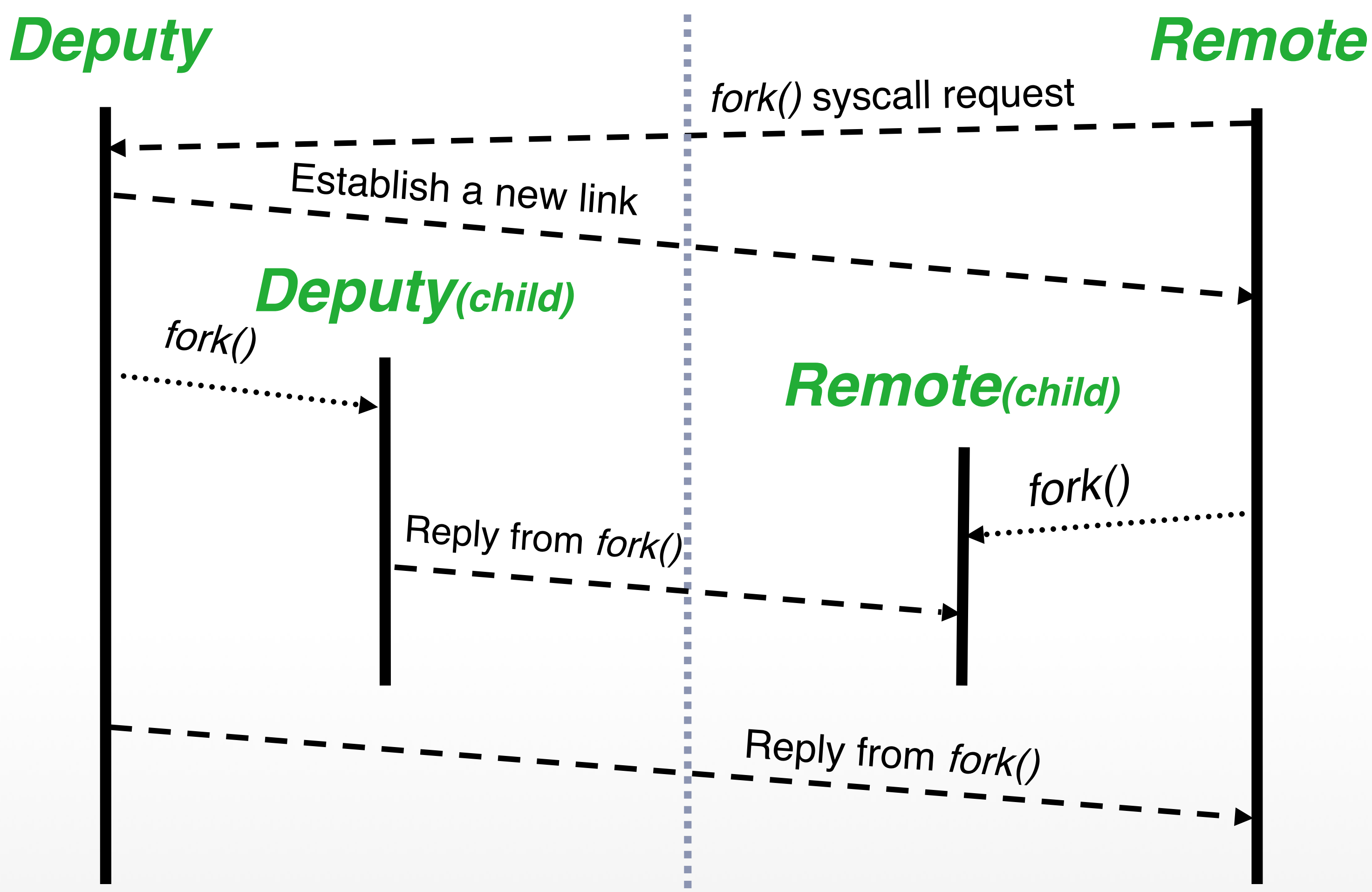
Process migration - the home node model



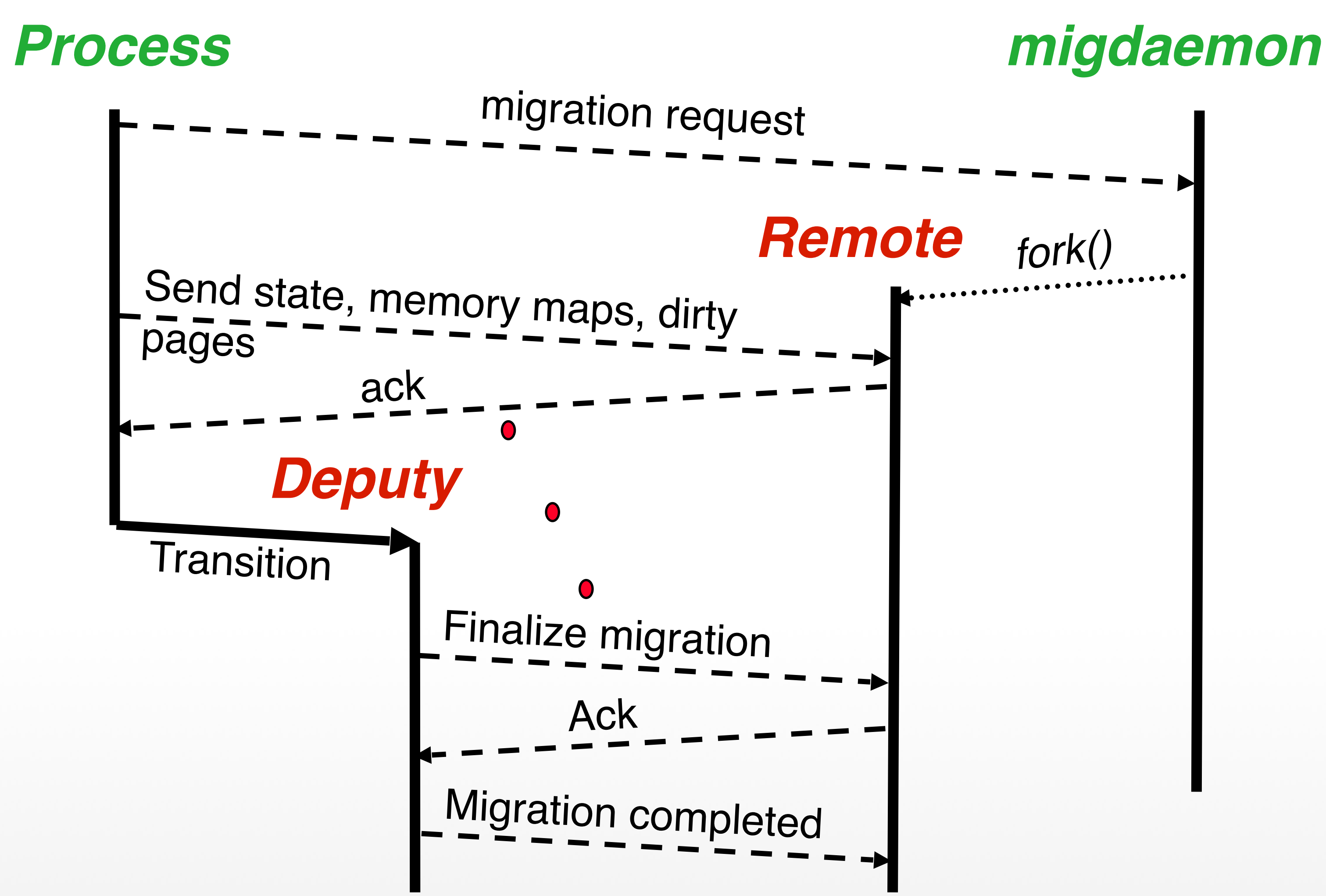
- Process migration – move the process context to a remote node
  - System context stay at "home" thus providing a single point of entry
- Process partition preserves the user's run-time environment
  - Users need not care where their process are running

Copyright © Amnon Barak 2011

FORK IN MOSIX



PROCESS MIGRATION IN MOSIX

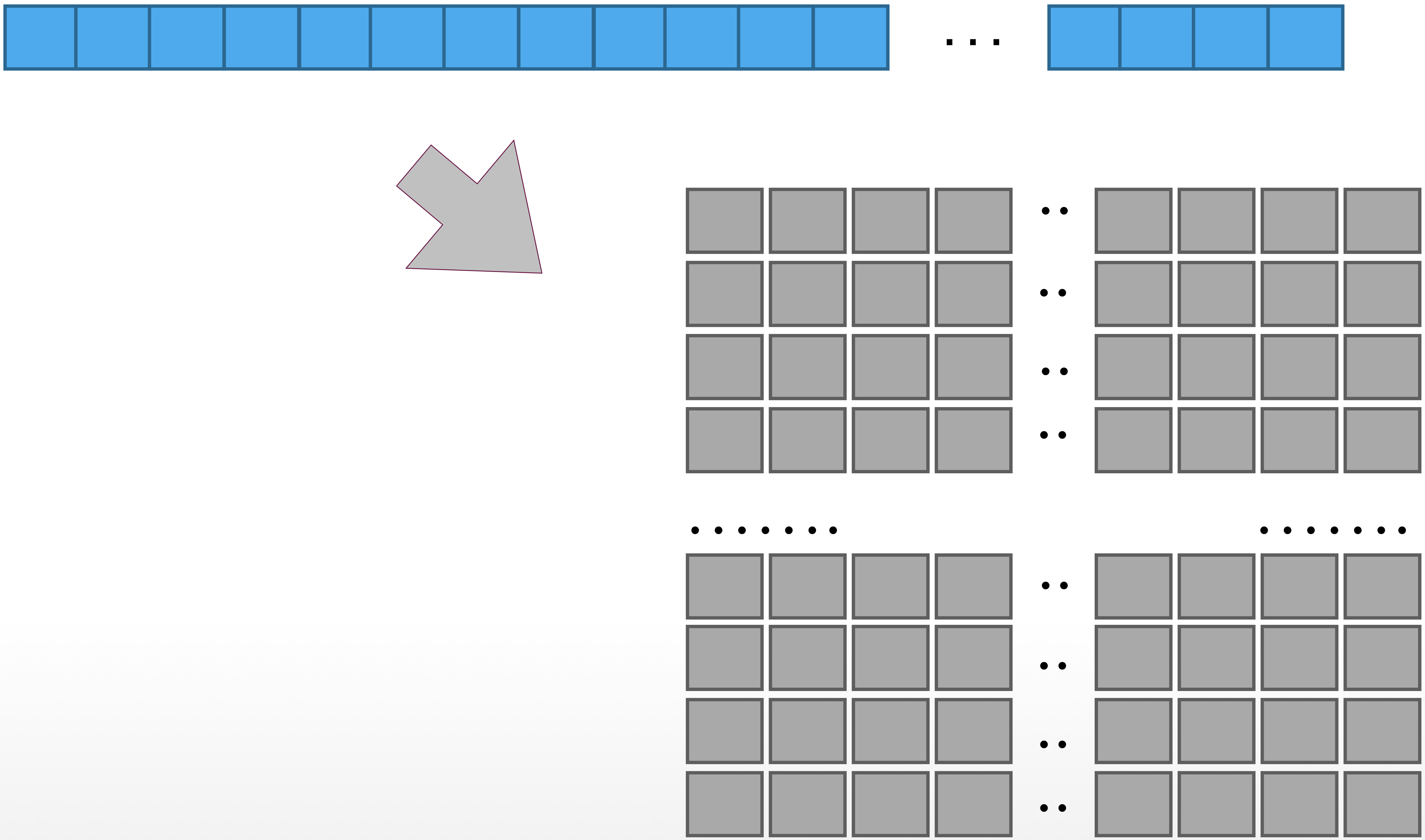


Distributed bulletin board

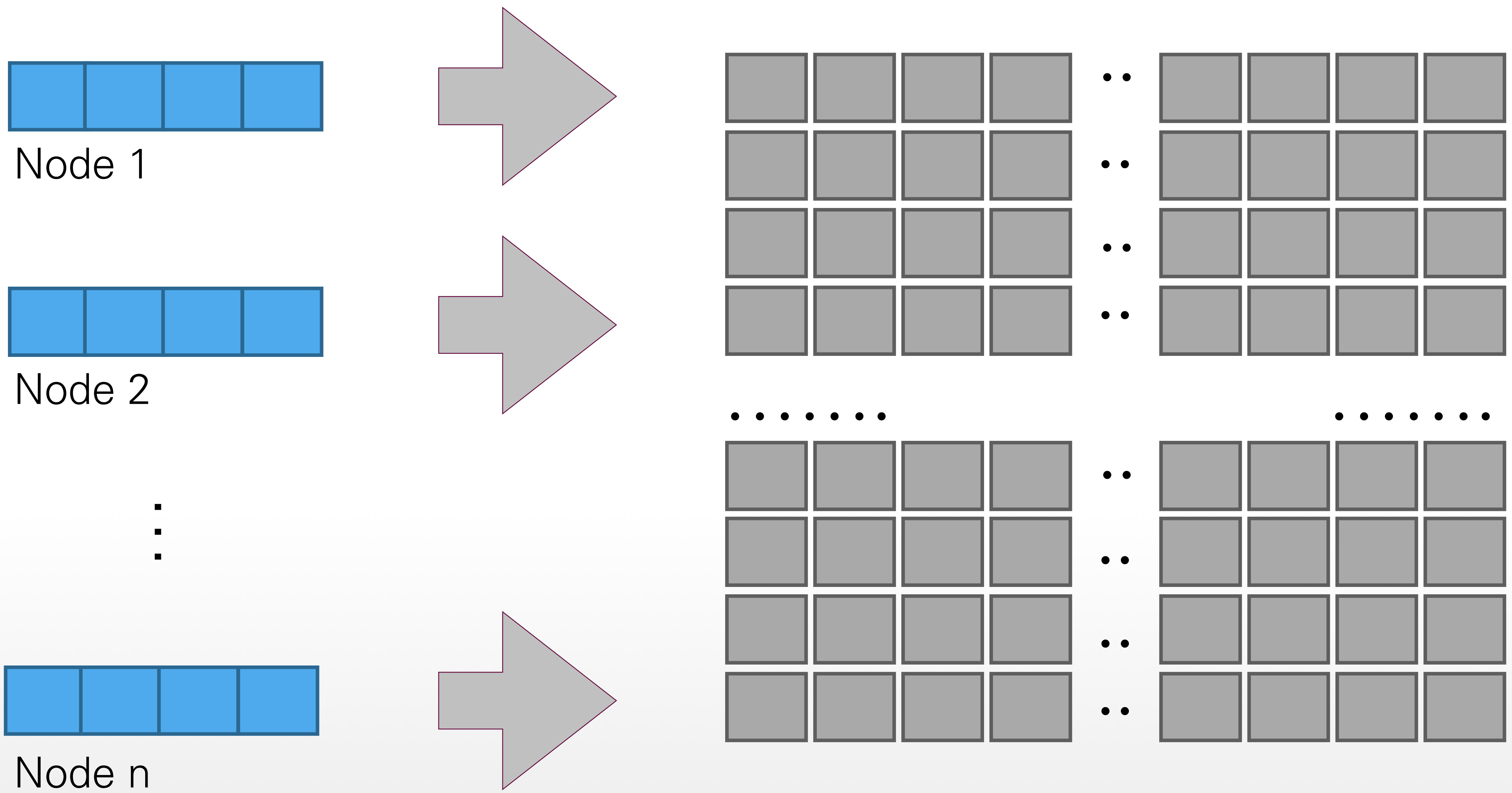
- **An n node cluster/Cloud system**
  - **Decentralized control**
  - **Nodes can fail at any time**
- ***Each node maintains a data structure (vector) with an entry about selected (or all) the nodes***
- **Each entry contains:**
  - **State of the resources of the corresponding node, e.g. load**
  - **Age of the information (tune to the local clock)**
- **The vector is used by each node as a distributed bulletin board**
  - **Provides information about allocation of new processes**

Copyright © Amnon Barak 2011

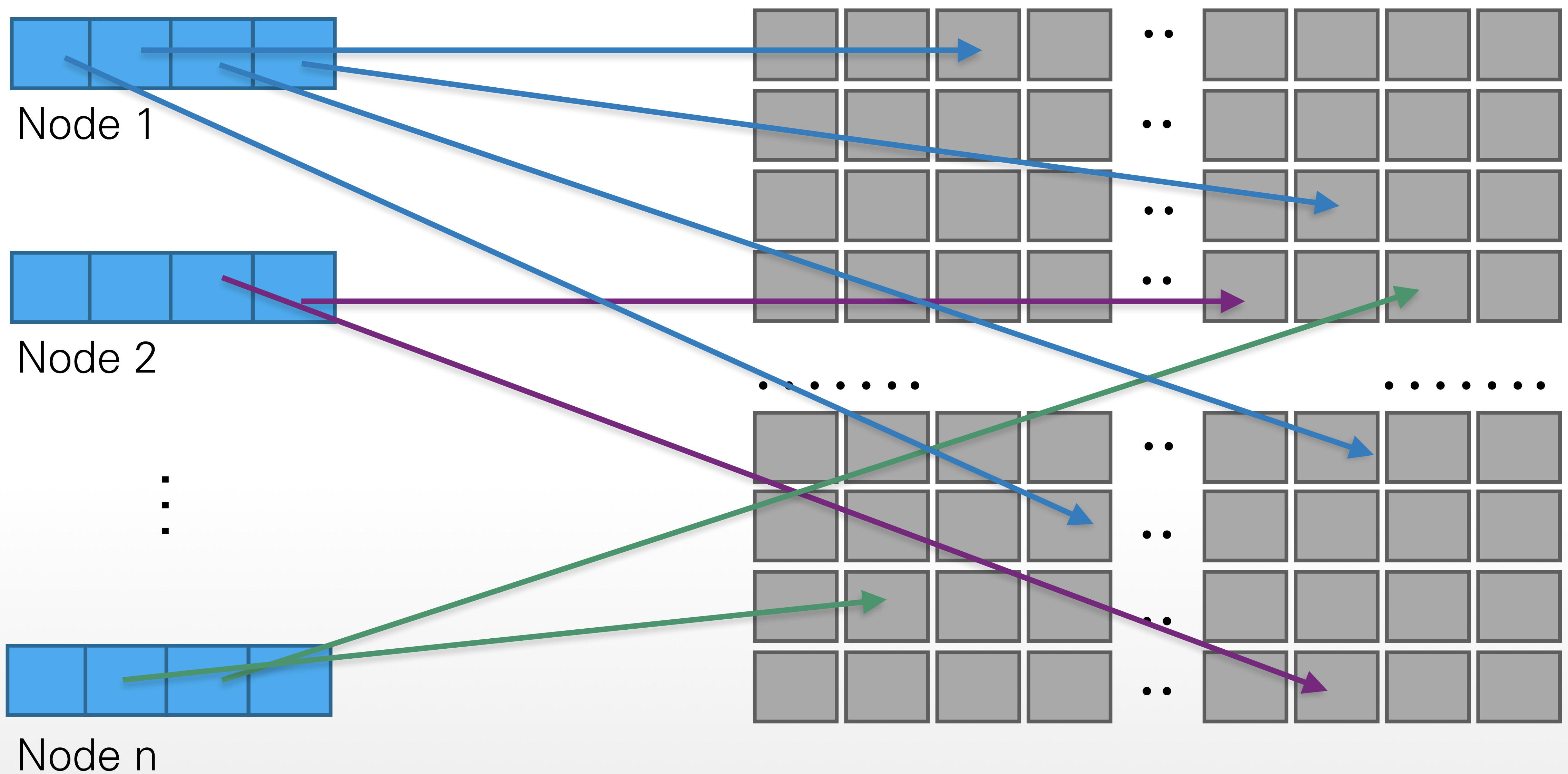
CENTRALIZED GLOBAL STATE



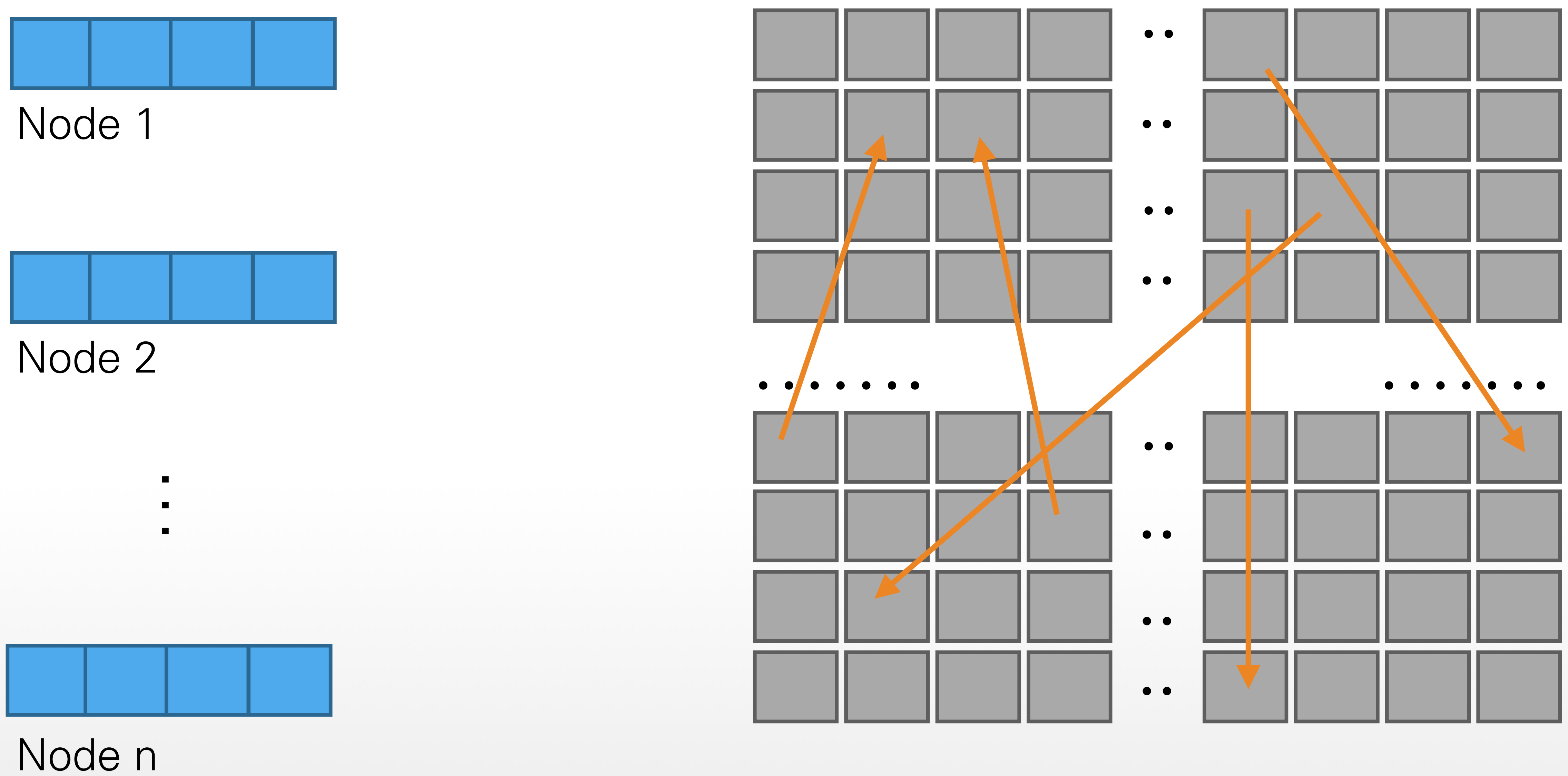
DECENTRALIZED GLOBAL STATE



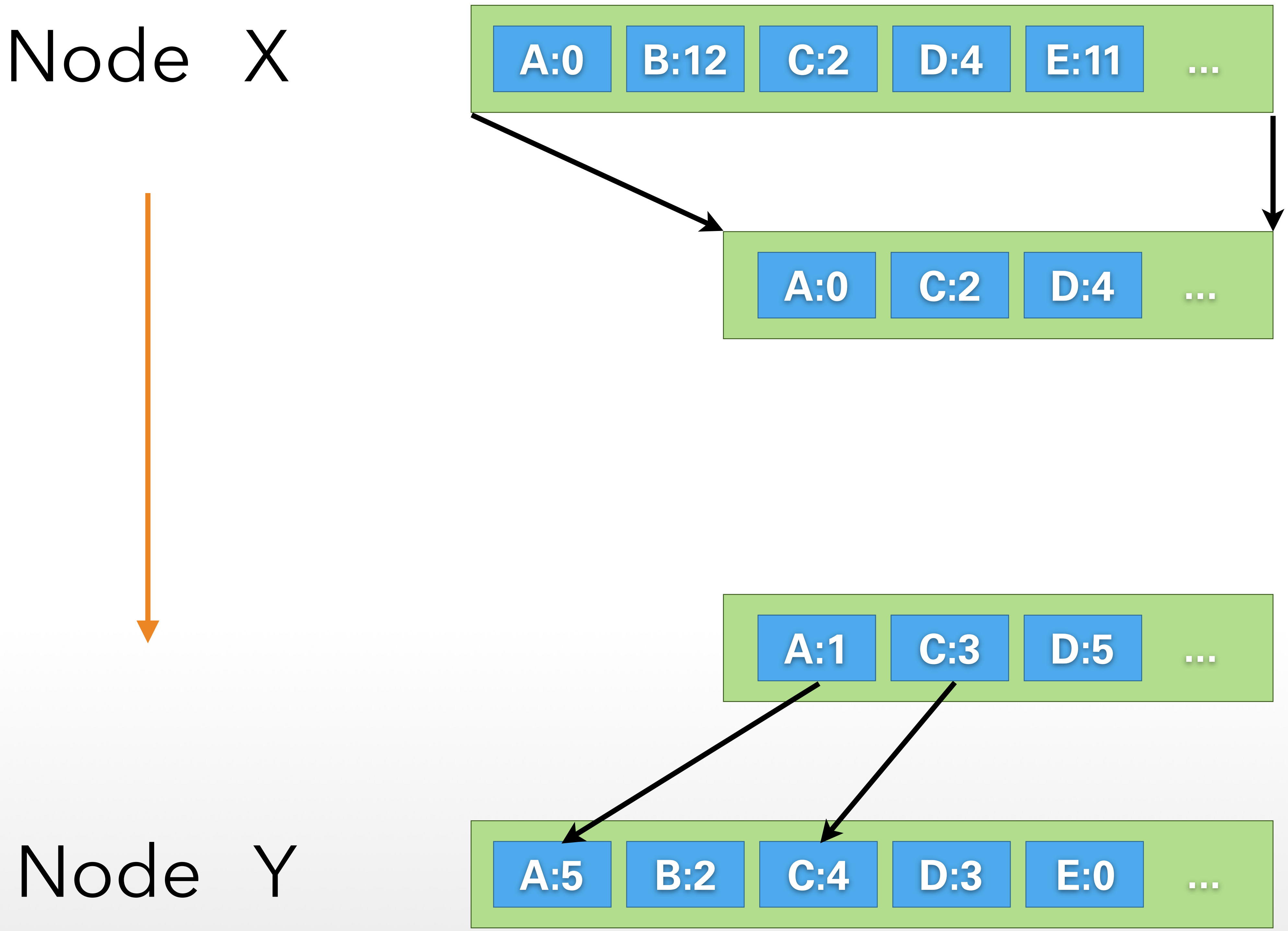
DECENTRALIZED GLOBAL STATE



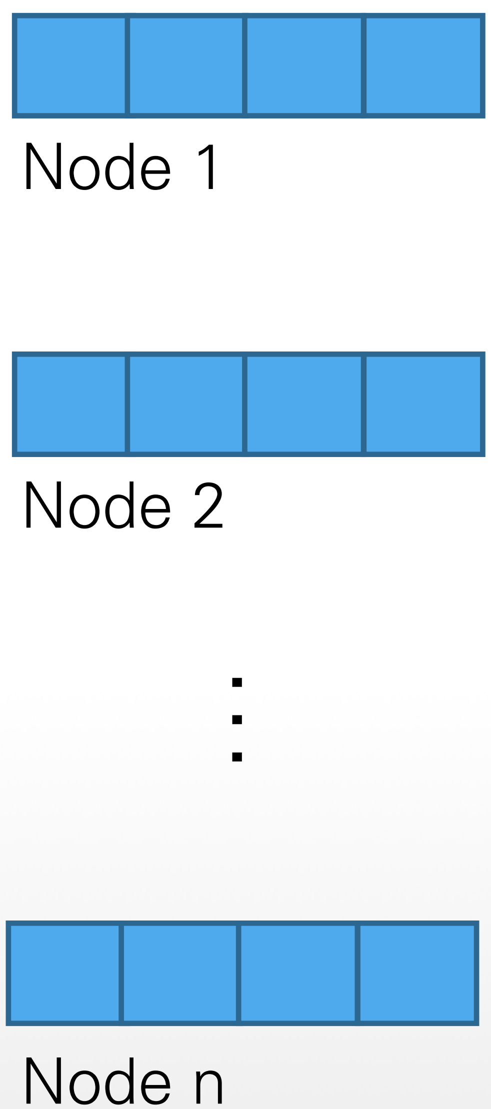
GOSSIP



GOSSIP



WWW



When

M: load difference discovered
anomaly discovered
anticipated

Where

M: memory, cycles, comm
consider topology
application knowledge

Which

M: past predicts future
application knowledge

Load balancing algorithms

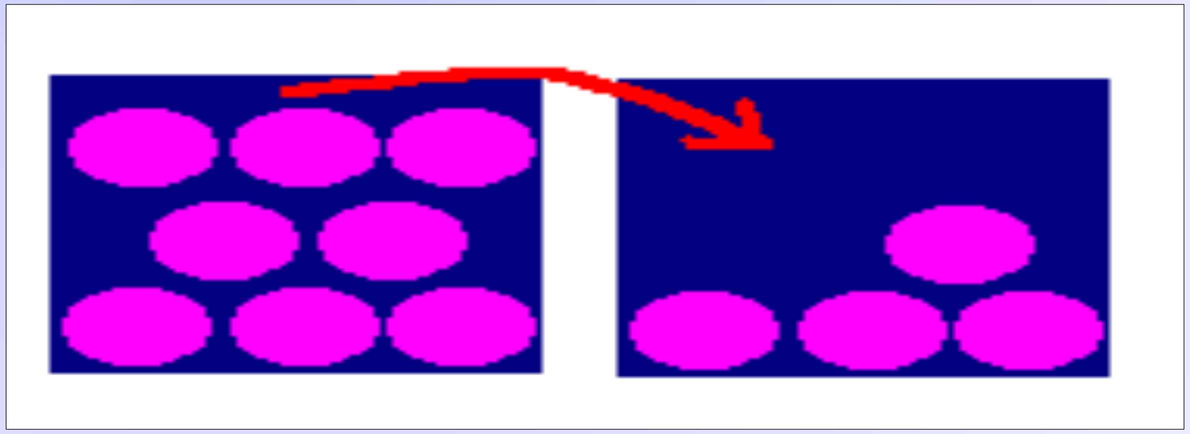
- When - Load difference between a pair of nodes is above a threshold value
- Which - Oldest process (assumes past-repeat)
- Where - To the known node with the lowest load
- Many other heuristics

- Performance: our online algorithm is only ~2% slower than the optimal algorithm (which has complete information about all the processes)

Copyright © Amnon Barak 2011

Memory ushering

- **Heuristics: initiate process migration from a node with no free memory to a node with available free memory**
- **Useful: when non-uniform memory usage (many users) or nodes with different memory sizes**
- **Overrides load-balancing**



- Recall: **placement problem is NP-hard**

Copyright © Amnon Barak 2011

Memory ushering algorithm

- **When** - free memory drops below a threshold
- **Where** - the node with the lowest load, to avoid unnecessary follow-up migrations
- **Which** - smallest process that brings node under threshold
  - To reduce the communication overhead

Copyright © Amnon Barak 2011

PRECEDENCE

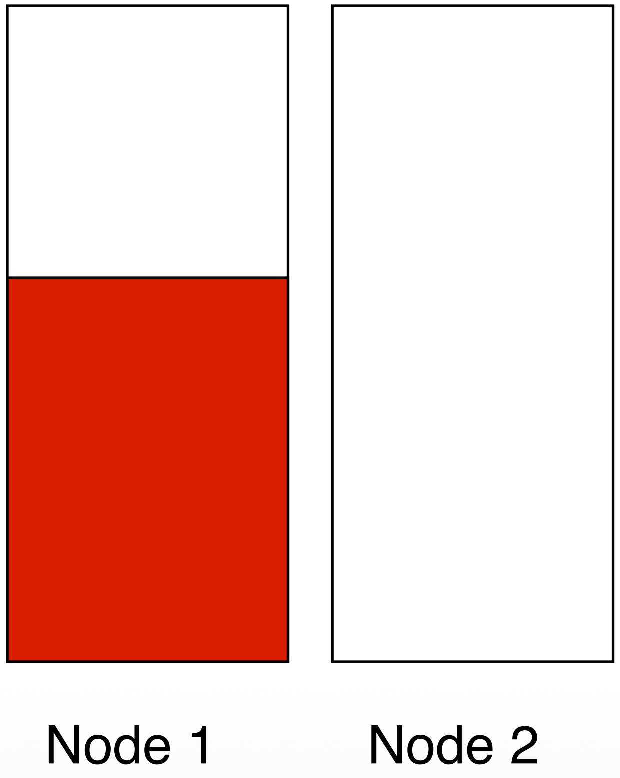
- memory
- cpu load
- IPC

TECHNISCHE UNIVERSITÄT DRESDEN

SOME PRACTICAL PROBLEMS

- flooding
  all processes jump to one new empty node
  => decide immediately before migration commitment
  extra communication, piggy packed
- ping pong
  if thresholds are very close, processes moved back and forth
  => tell a little higher load than real

PING PONG



One process two nodes

Scenario:
compare load on nodes 1 and 2
node 1 moves process to node 2

Solutions:
add one + little bit to load
average over time

Solves short peaks problem as well
(short cron processes)

LESSONS

- execution/communication time jitter matters (Amdahl)
- HPC approaches: partition ./. balance
- dynamic balance components:
  migration mechanism,
  information bulletin,
  decision: which, when, where