Proposed Research Topic:

# Zero-Config Automatic Parallel Simulation

András Varga, Levente Mészáros
OMNeT++ Core Team

# “Proposed Research Topic”

- NOT finished research.
- NOT even research underway.

- A promising research topic for those looking for one.
  - (We see potential in the idea and find it exciting, but we don't have the resources [mostly, time] to elaborate it in-house.)

- Why?
  - Practically VERY useful
    - **Everybody would love their simulations to run X times faster on common hardware!**
  - Doable
    - We have already spent some time trying out the idea and proven (at least to ourselves) that it is feasible and the approach outlined here can be made to work.
  - Novel
    - Related research only took of a few years ago
  - Plenty of questions and degrees of freedom
    - publication opportunities!

# Two Questions

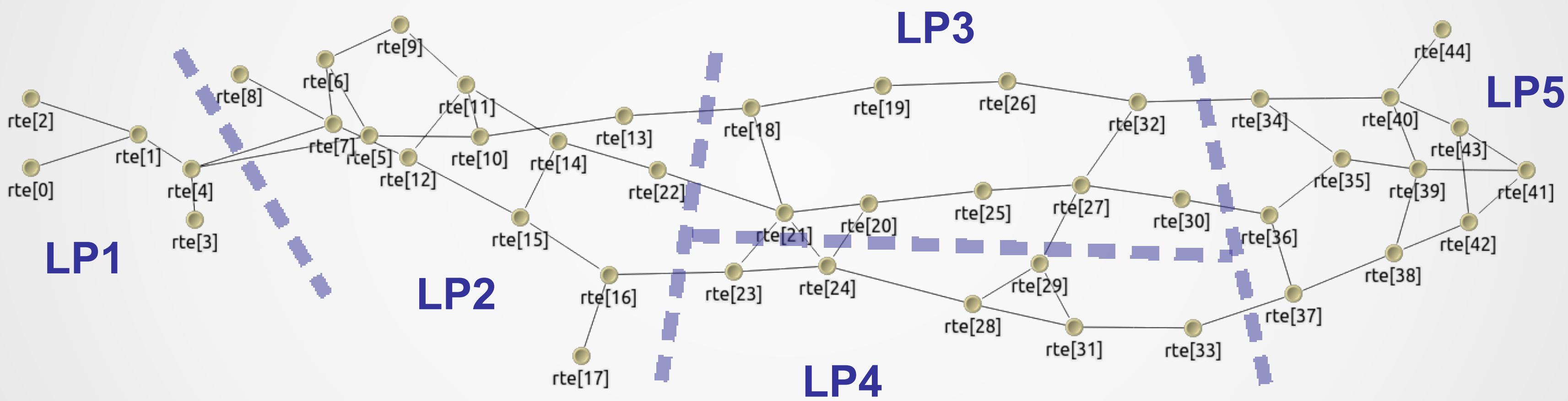
What is zero-configuration parallel simulation?
(and why is it called so?)

Doesn't OMNeT++ have parallel simulation support already...?

# OMNeT++ Parallel Simulation Support

## 1. Partition the network

- Each partition will be run in a separate LP (logical process)




Partition – how...?

- interaction between partitions should be *minimal*
- link delays across partitions should be *high*
- workload should be *evenly* distributed

# OMNeT++ Parallel Simulation Support

## 2. Describe this partitioning in omnetpp.ini

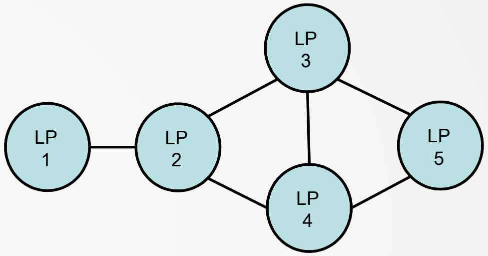
```
[General]
parallel-simulation = true
*.rte[0..4].partition-id = 0
*.rte[5..17].partition-id = 1
*.rte[22].partition-id = 1
*.rte[18..21].partition-id = 2
*.rte[23..24].partition-id = 2
...
```

Here's the "configuration"

# OMNeT++ Parallel Simulation Support

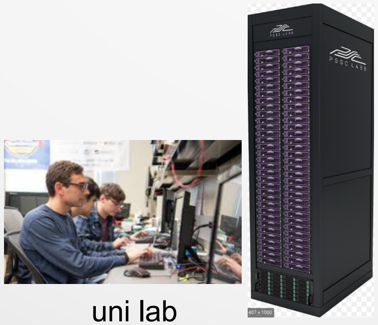
## 3. Run the simulation on a multiprocessor

- Each partition (logical process, LP) will be a separate simulation process
- Executing on its own CPU (or core)
- Communication over MPI




- Hardware: multicore laptop/desktop, HPC cluster
  (low communication latency is essential, more so than bandwidth)

multicore
laptop / desktop



uni lab
HPC facility

supercomputer center

commercial services

# OMNeT++ Parallel Simulation Support

Limitations:

- ~~Global variables~~
- ~~Accessing modules in other partitions~~
- ~~Method calls across partition boundaries~~
- ~~Simsignal propagation across partition boundaries~~
- ~~Moving modules to a different partition (?)~~

Overhead:

communication overhead

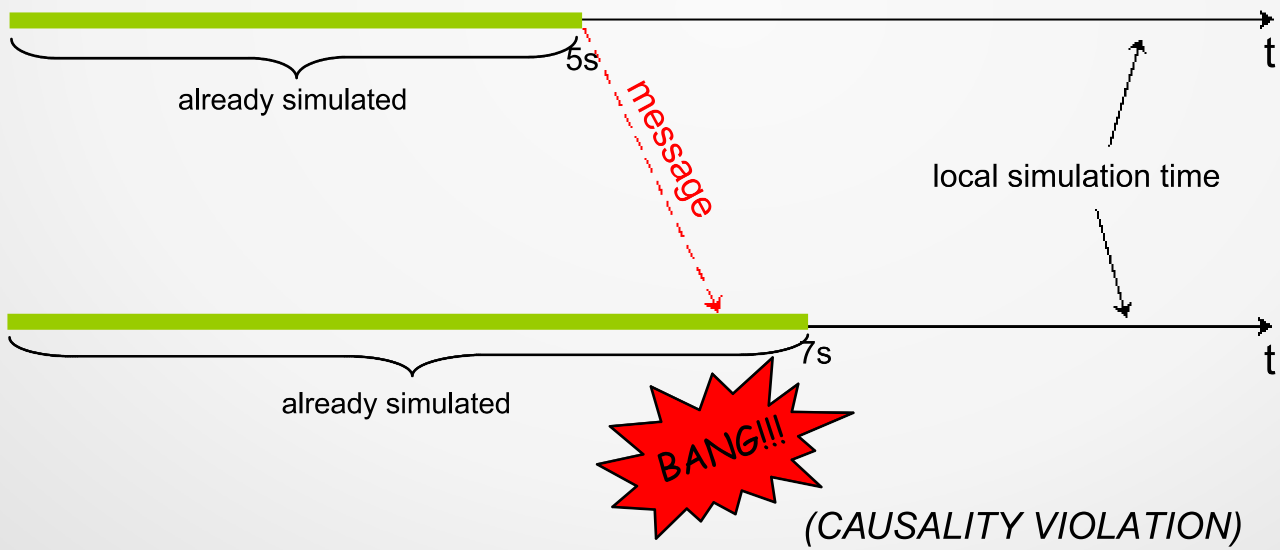
synchronization overhead
(lookahead is critical)

Can run on clusters (distributed memory multiprocessors) too, but on multicore CPUs, doesn't properly take advantage of shared memory

# OMNeT++ Parallel Simulation Support

## Why synchronization is needed

Example: Two LPs, each of them executing events independently in timestamp order, and sending events to each other



# Maintaining Event Causality

- **The future should not affect the past.**
  That is, processing an event must not have an effect on events with smaller timestamps*.
  - This is the main problem of Parallel Discrete Event Simulation (PDES).

* More precisely, the *(timestamp,priority,insertOrder)* triplet is used by OMNeT++ for ordering events

# PDES Approaches

## Conservative

- **do not allow causality violations**
- *example: null-message protocol, a.k.a Chandy-Misra-Bryant*

- performance: ”lives or dies by the lookahead” (e.g. link delays)

- implementation: straightforward

- chosen by OMNeT++

## Optimistic

- **allow incausalities, detect them, and repair them by rolling back**
- *example: Time Warp algorithm*

- *performance: may suffer from excessive rollbacks*

- implementation: complicated protocol (anti-messages etc), laborious implementation (state saving & restoration needs to be implemented in each and every model component, as C++ provides no STM solution)

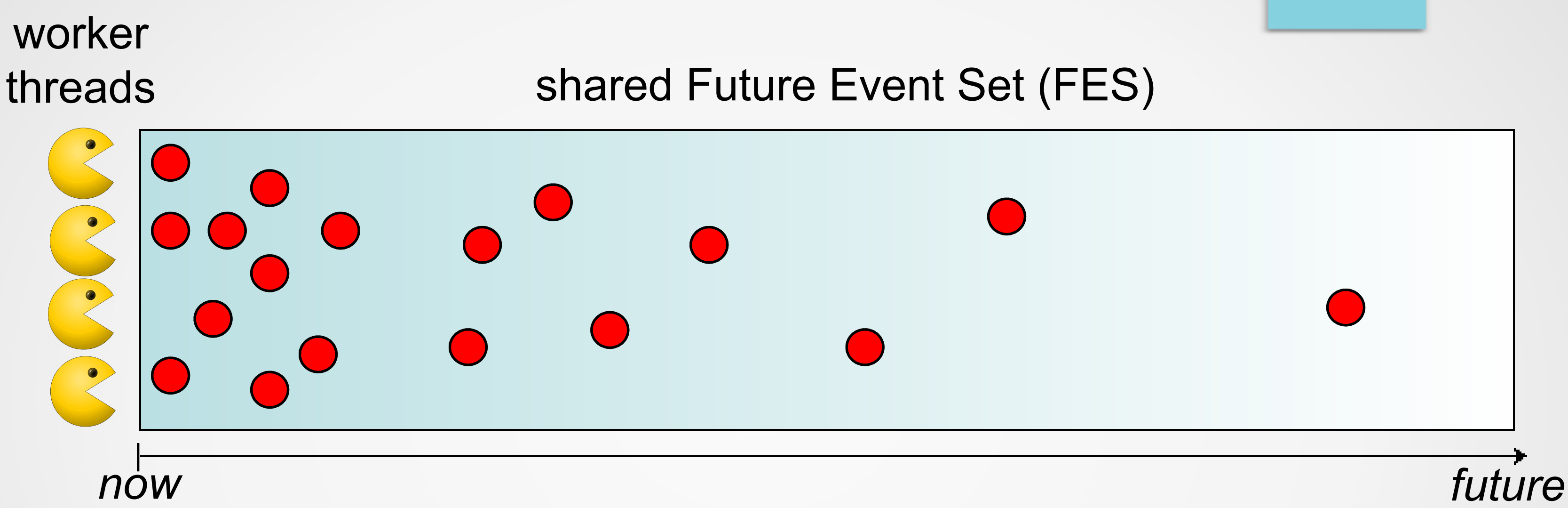
- so only necessary if *Conservative* cannot fully utilize the hardware

# Diverging From the LP-Based Approach

## Why?

- Advances in hardware
  - increase in single-core performance slowed, number of cores steadily increasing instead
    - 4 cores standard, 8/12/16+ cores, etc. available ⇨HPC clusters less needed
  - memory abounds
    - 8/16G is standard, 32/64G and up easily available ⇨ *“distribute memory requirements”* argument for LP-based PDES no longer holds
- Limitations of LP approach
  - coding limitations (no access across partitions, etc.)
  - overhead (communication, serialization; unable to take full advantage of shared memory systems)
  - inconvenience (mpi_run, etc)

# Multi-Threaded Simulation

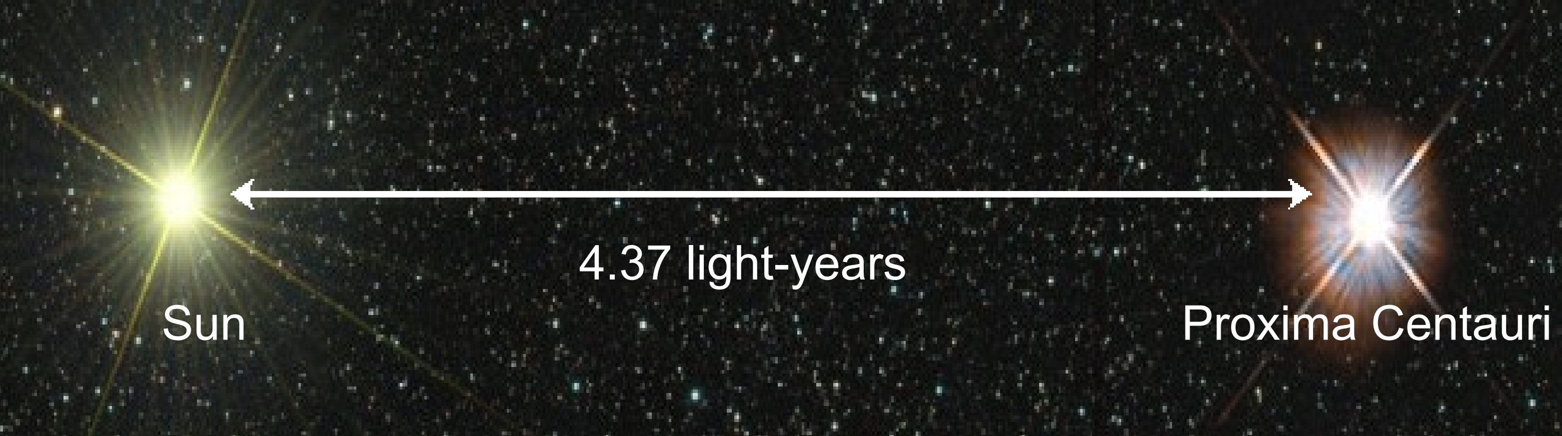



*Worker threads take events from a shared FES, process them, and insert the resulting events into the FES.*

Challenges:

1. Event causality must be kept
2. Concurrent access of data structures (FES, simulation objects)

# Event Causality

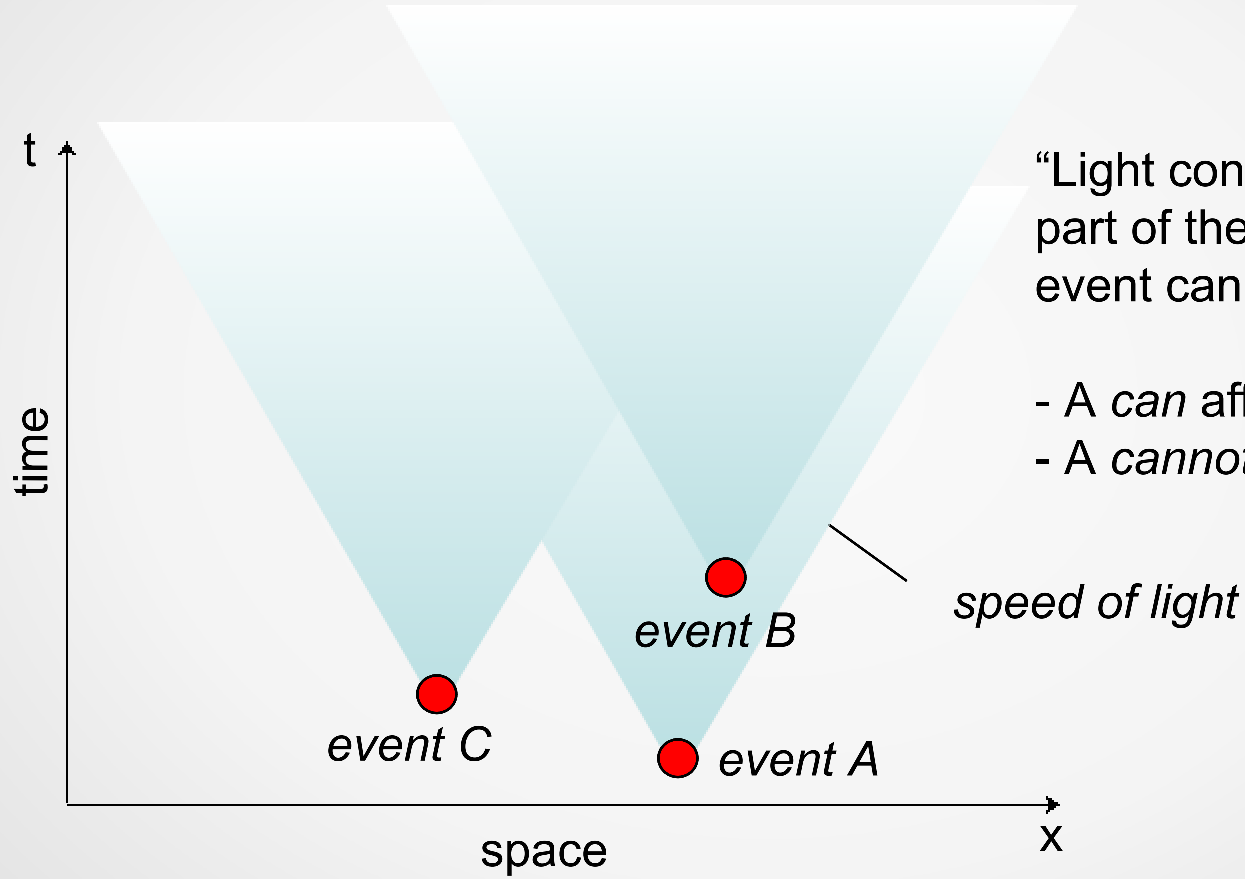



“What if it exploded right now...?”

“... or 4.3 years ago?”

– Simultanous events at both cannot affect each other
– Moreover: if time difference < 4.37 years → events cannot affect each other

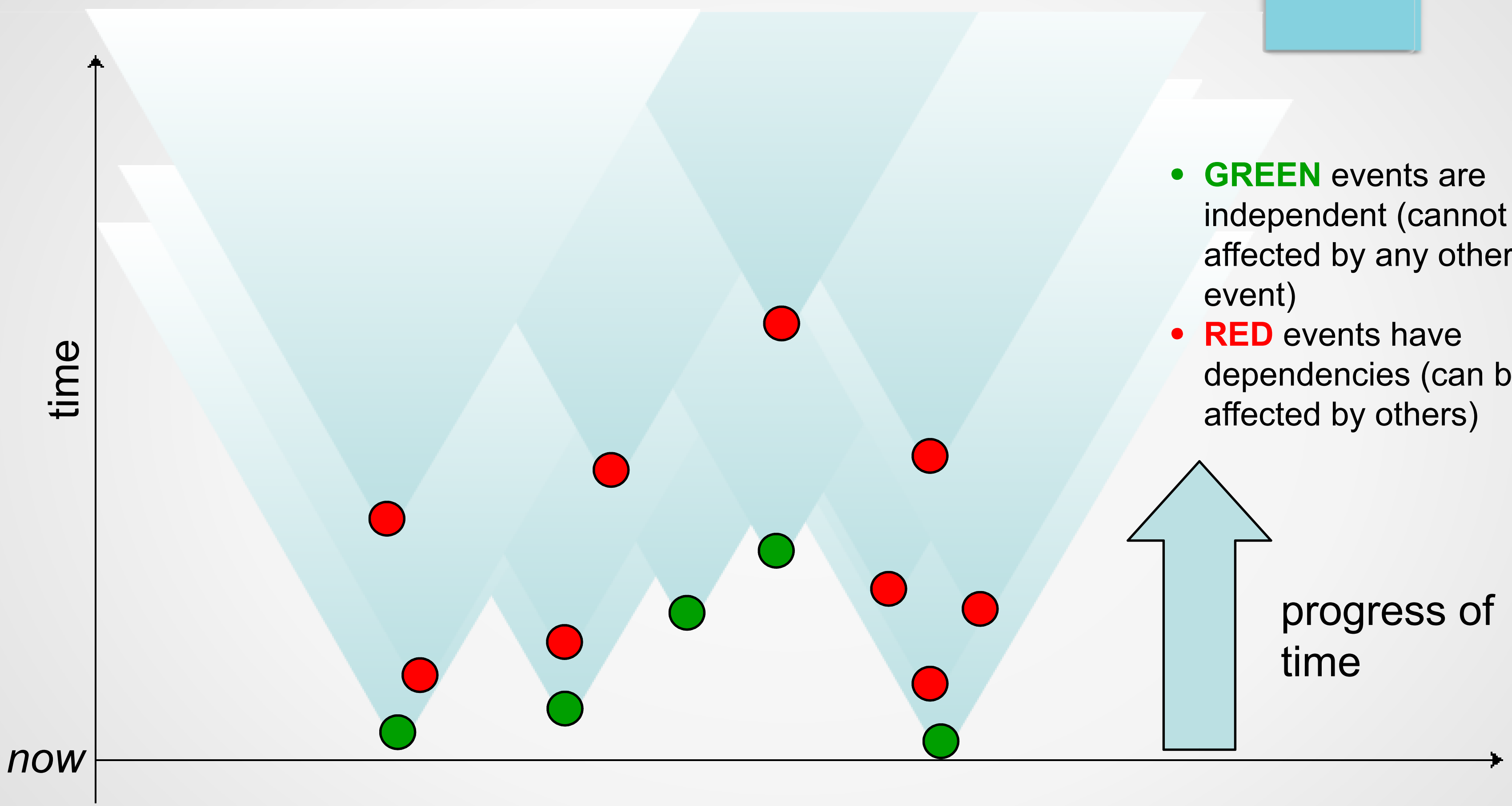
# Visualization: Space-Time Diagram




"Light cone" illustrates which part of the space-time an event can affect.

- A *can* affect B
- A *cannot* affect C

# Event Coloring

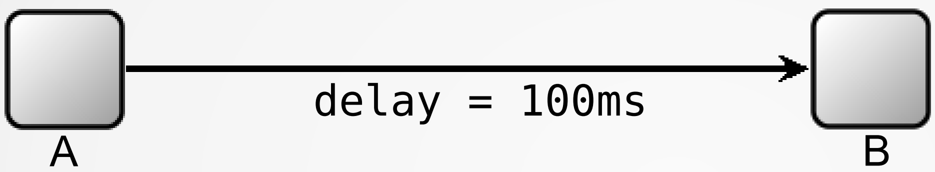



- **GREEN** events are independent (cannot be affected by any other event)
- **RED** events have dependencies (can be affected by others)

As time progresses: 1. green events stay green; 2. red events may turn green

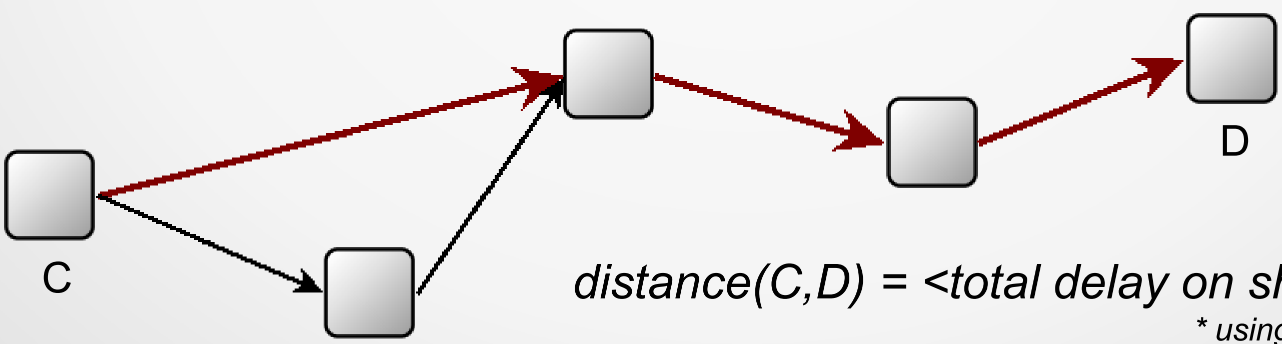
# Applying to Simulation

Between modules, if only interaction is message passing:




*distance(A,B) = 100ms*
*distance(B,A) = inf*

*“100 light-milliseconds distance A-to-B”*




*distance(C,D) = <total delay on shortest* path>*

** using delay as metric*

# Zero-Config Parallel Simulation

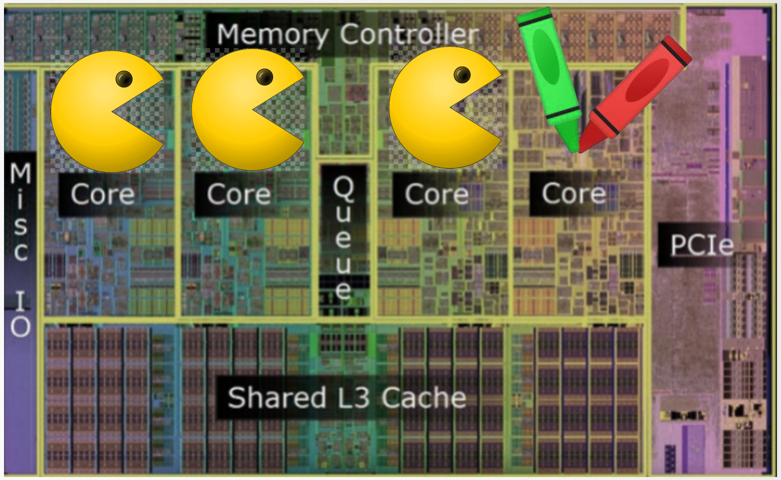
- Meaning of coloring:
  - **Green** events can be executed in concurrently
  - **Red** events cannot

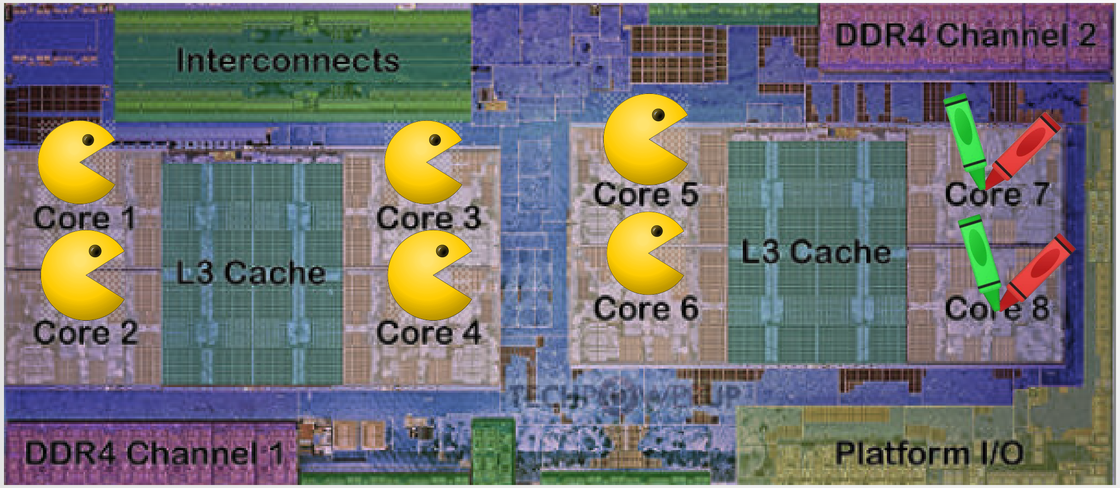
- During simulation:
  - **Worker threads** process **green** events
  - **Colorer** continually works on turning more events **green**

# Mapping to Hardware

Coloring algorithm may run continuously in the background. [when done, wait for change in FES]

Separate thread/core can be dedicated to coloring




Coloring algorithm can be parallel in itself (if that's the bottleneck)

# Coloring Algorithm

Pseudocode:

```
for each red event in the FES:
    if it's not in any other event's "light cone":
        mark it as green
```

A little more formally:

```
for each red event E1 in module M1 in the FES:
    T := (minimum of arrivalTime(E2) + distance(M2, M1) \
              for each event E2 in module M2 before E1 in the FES)
    if arrivalTime(E1) < T:
        mark E1 as green
```

T: time of earliest possible effect from other modules
distance(M2, M1): total delay on shortest path from M2 to M1

# The distance() Function

- Precompute
  - Then keep up-to-date with topology changes

- Store as matrix
  - Requires $N^2$ space for $N$ modules
  - *Optimization possibility:* represent zero-delay module groups as one entry (row/col)
    - In INET, almost all modules within a host or router form such a zero-delay group → reduces matrix size

# Non-Message Dependencies

- Method call: instantaneous effect
  - Action: *“A performs* `B->f()`*”*
  - Setters: *A→B* dependence*: distance(A,B)=0*
    - like a zero-delay *A→B* message sending
  - *Getters: B→A* dependence*: distance(B,A)=0*
  - Mixed: mutual dependence
- Global variable: instantaneous effect
  - *A* writes, *B* reads: *A→B* dependence
- Signals
  - Listeners are “method calls in disguise”
    - as emit() indirectly invokes listeners
  - For all *E* emitter and *L* listener pairs: *E→L dependence, i.e. distance(E,L)=0*

# Implementing the Colorer

- Pseudocode shows a *naïve* algorithm
  - Looks at all events every time
    - For performance, it should be **incremental**

- Issue:

<u>Worker thread:</u>

```
msg = fes->pop();
mod->handleMessage(msg);

handleMessage(msg) {
     delete msg /
     send(msg,..) /
     scheduleAt(t,msg)
}
```

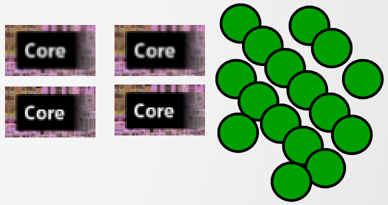
<u>Colorer:</u> Removing an event and adding consequence events should happen <u>*atomically*</u>!

<u>Resolution</u>: Colorer must work on a <u>*view*</u> of the FES, not on the FES itself!

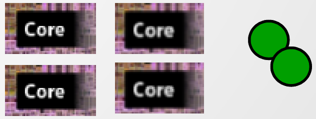
# Worker Thread Scheduling

How should worker threads pick from the pool of green events?

- Grabbing >1 event at a time may reduce blocking overhead
- **If #events > #cores**:
  - in which order to serve them?
  - order affects performance




- **If #green < #cores:**
  - eager assignment?
  - being eager may not always be the best strategy
    - may pay off to wait for new events that contribute more to simulation progress




- Further observations?

# Concurrent Access

- FES is under heavy concurrent access
  - locking
  - lock-free data structures
- Simulation model and state
  - Challenge: Cross-module method calls
    - Relaxing: If events within a (compound) module are NOT processed concurrently, inter-node accesses don't need to be protected
  - Simsignals: Method calls in disguise!
    - Emitting a signal indirectly invokes the listeners
    - Listeners need to be protected against concurent accesses
  - Model code needs to be instrumented for zero-config parsim!
- Simulation kernel and infrastructure
  - If model is static -- no protection needed
  - Dynamic module creation and other model changes
  - Result filters/recorders also need to be protected

# Assessment on INET

“Are there enough green events in “normal” simulations?”

**Experiment:** We added a simple version of Colorer to an otherwise vanilla OMNeT++ INET simulation.

**Result:** Usually 4-5 green events in the FES in a network of 4 LANS, 4 hosts/LAN. This was a small simulation; we expect the number of green events to scale linearly with the size of the simulation ⇨ enough to keep all CPU cores busy.

# Research Questions

Topics open to research:

- Choice of FES data structure
- Efficient Colorer algorithm
- Worker thread scheduling

**If** you are interested, please contact us!

# END

**(QUESTIONS?)**