Programmability and Performance of Parallel ECS-based Simulation of Multi-Agent Exploration Models

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Event and Cross State (ECS) Dependency

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  - interactions happen via timestamped event exchanges among LPs
  - each LP keeps a portion of the whole simulation state

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- In sequential DES simulation, so far so good.
- What if this model is executed in a Parallel DES environment?
  - Think of Optimistic Synchronization!

Step 1: Materializing Cross-State Dependencies

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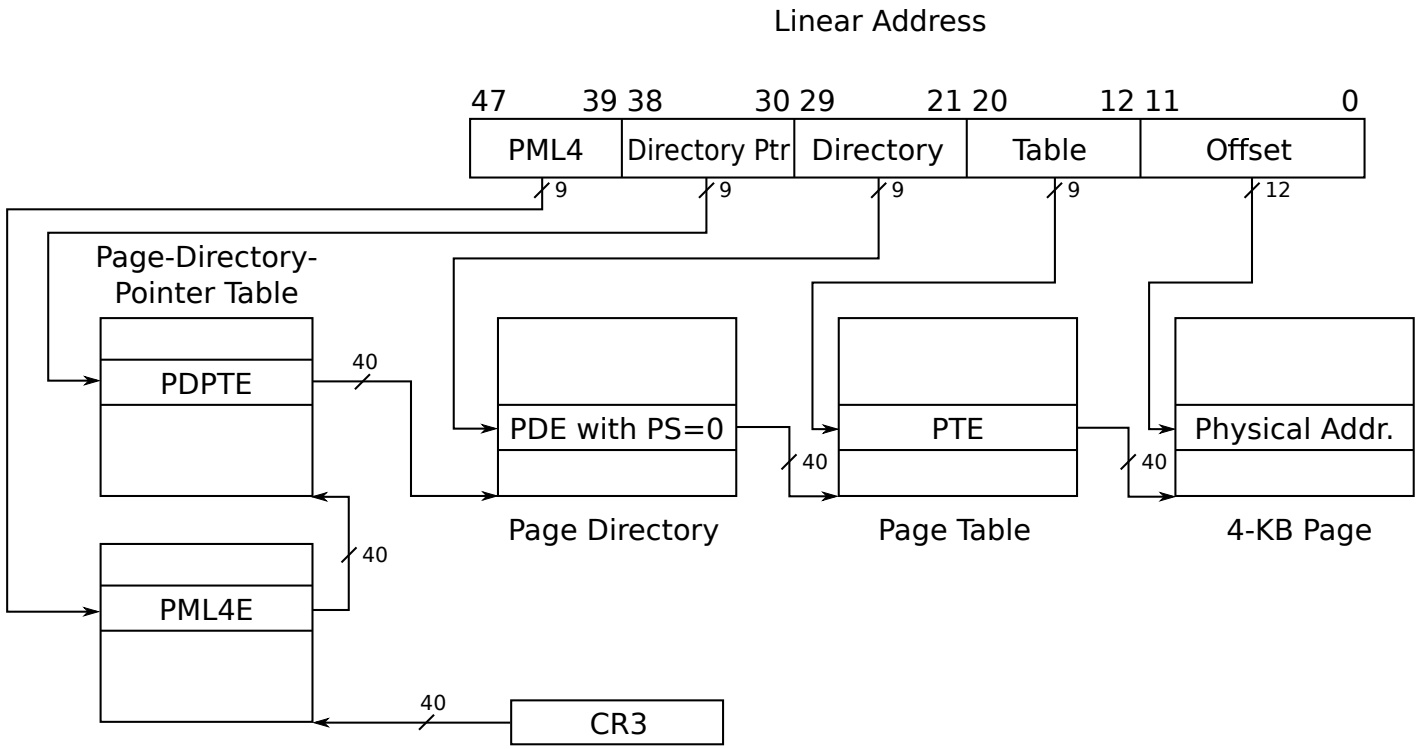
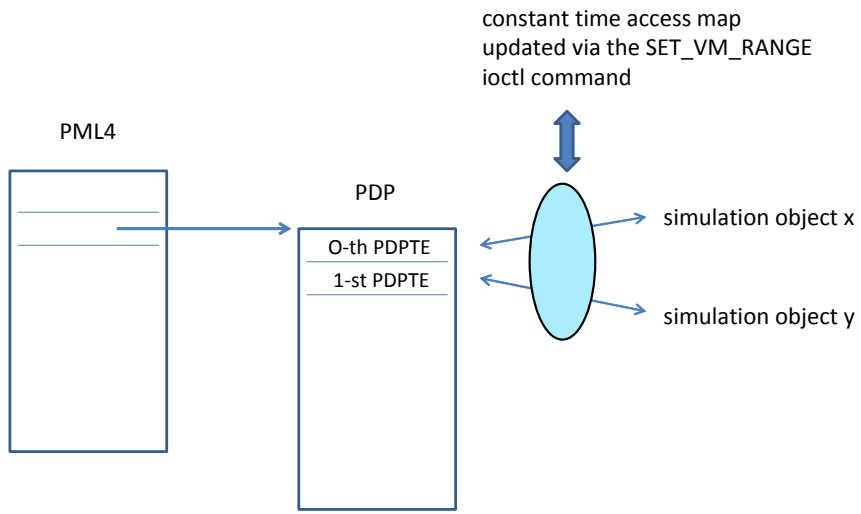


Memory Allocation Policy

- LPs use virtual memory according to *stocks*
- Memory requests are intercepted via malloc wrappers (DyMeLoR)
- Upon the first request, an interval of page-aligned virtual memory addresses is reserved via `mmap` POSIX API (a *stock*)
- This is a set of empty-zero pages: a null byte is written to make the kernel actually allocate the chain of page tables
- One stock gives 1GB of available memory to each LP

Memory Access Management

- 99% handled via a Linux Kernel Module
- A LKM creates a device file accessible via `ioctl`
- `SET_VM_RANGE` command associates stocks with LPs
- A kernel-level map (accessible in constant time) is created:
  - Each stock is logically related to one entry of a PDP page-table
  - The id of the LP who the stock belongs to is registered



Memory Access Management

- When LP j accesses LP i's state, we could know that by the memory address
- We target SMP Simulation: memory protection is not an option
- Every worker thread is associated with a sibling PML4 entry:
  - They point same PDP entries...
  - ...but with different privileges!

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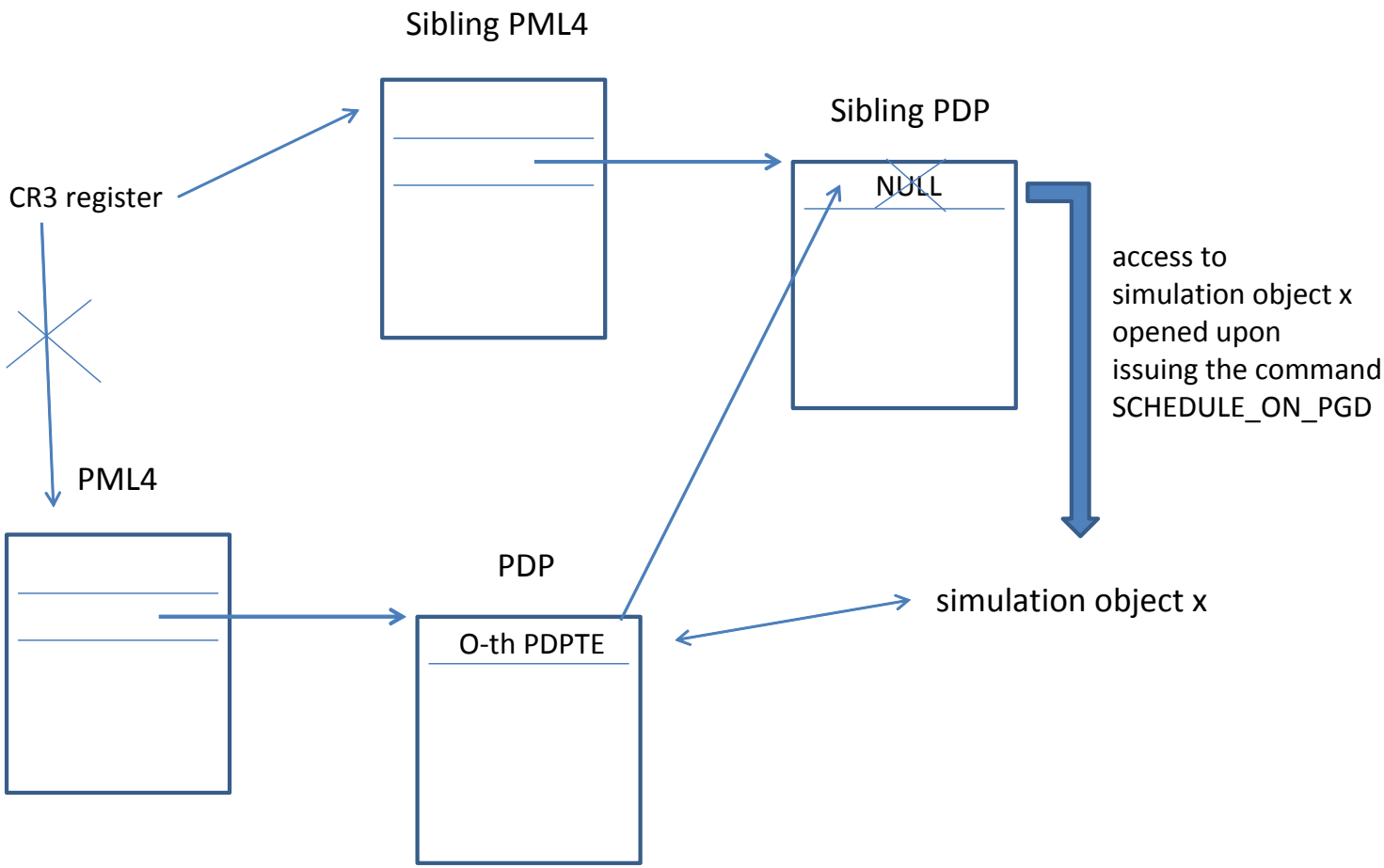
- The `SCHEDULE_ON_PGD` command brings the execution in *simulation-object mode*:
  - The only accessible stock is dispatched LP's one
  - This operation leads to a change in the `CR3` hardware register

Memory Access Management



Cross-State Dependency Materialization

- If other LPs' stocks are accessed, we have a memory fault
- This is the materialization of a Cross-State Dependency

- Yet, this page fault cannot be traditionally handled:
  - Memory has already be validated via `mmap` at simulation startup
  - The Linux kernel would simply reallocate new pages
  - For the same virtual page we would have multiple page table entries!

Step 2: Event and Cross-State Synchronization (ECS)

- At startup we change the IDT table to redirect the page-fault handler pointer to a specific ECS handler
- Upon a real segfault, the original handler is called
- Otherwise, the ECS handler pushes control back to user mode:
  - Execution goes back into *platform mode*
  - `CR3` is switched back to the original PML4 table
  - The simulation kernel can access any memory buffer required for supporting synchronization

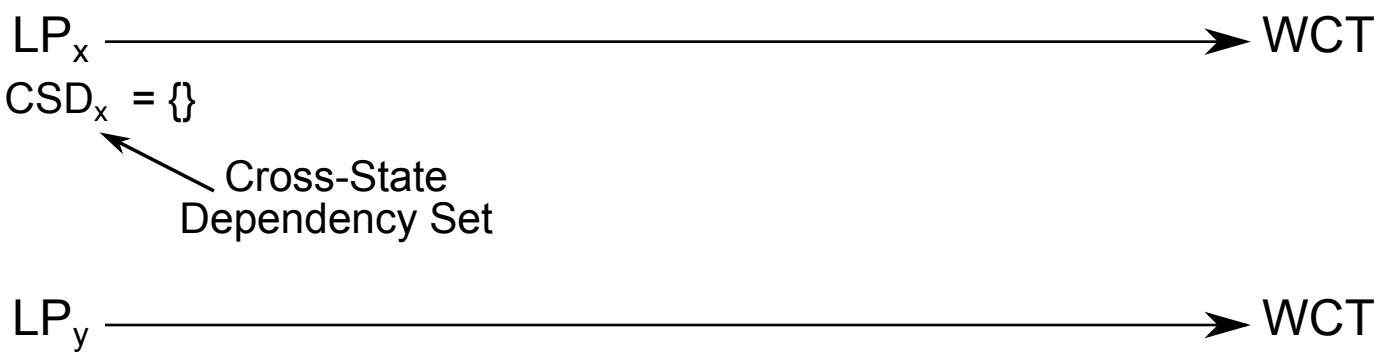
ECS System

Property

When a Cross-State Dependency is materialized at simulation time T, the involved LP observes the state snapshot that would have been observed in a sequential-run.

- To enforce this we introduce:
  - temporary LP blocking: the execution of an event can be suspended
  - *rendez-vous events*: system-level simulation events not causing state updates

ECS System



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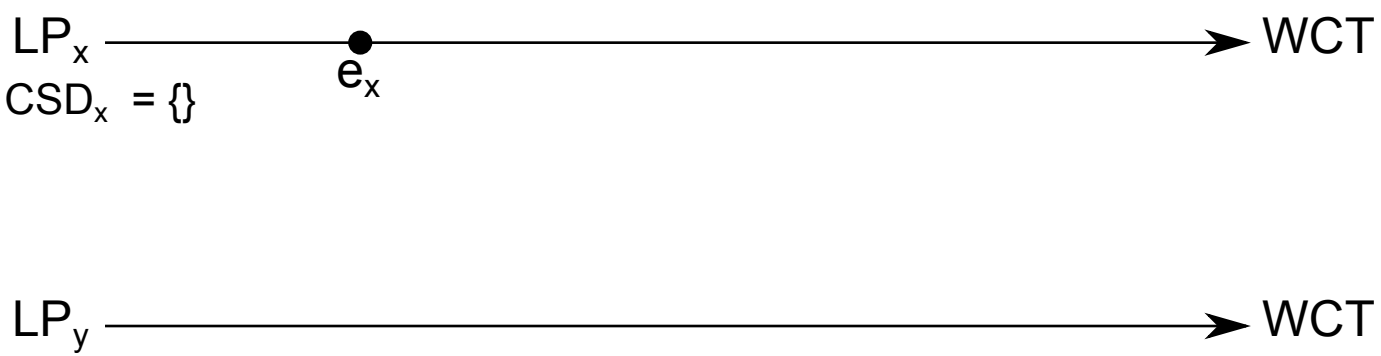

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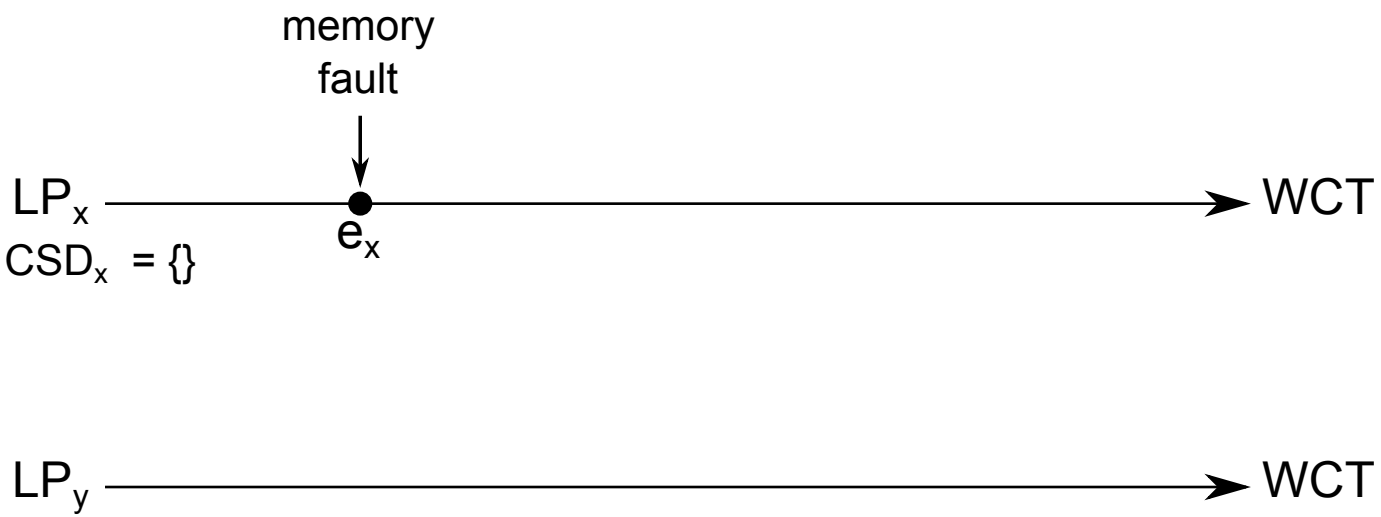

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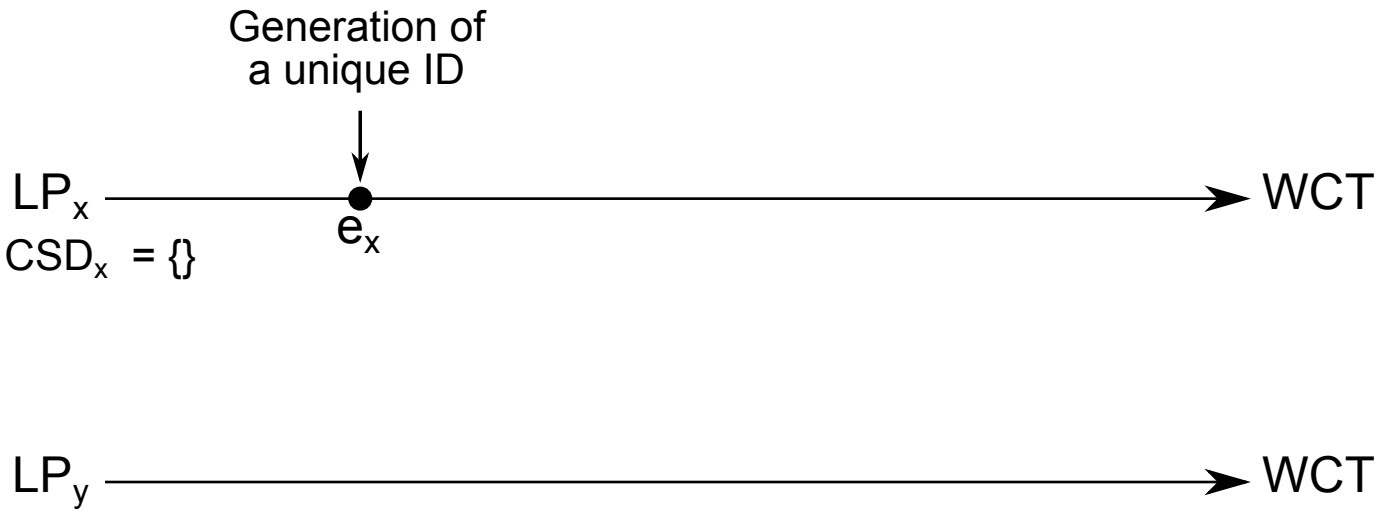

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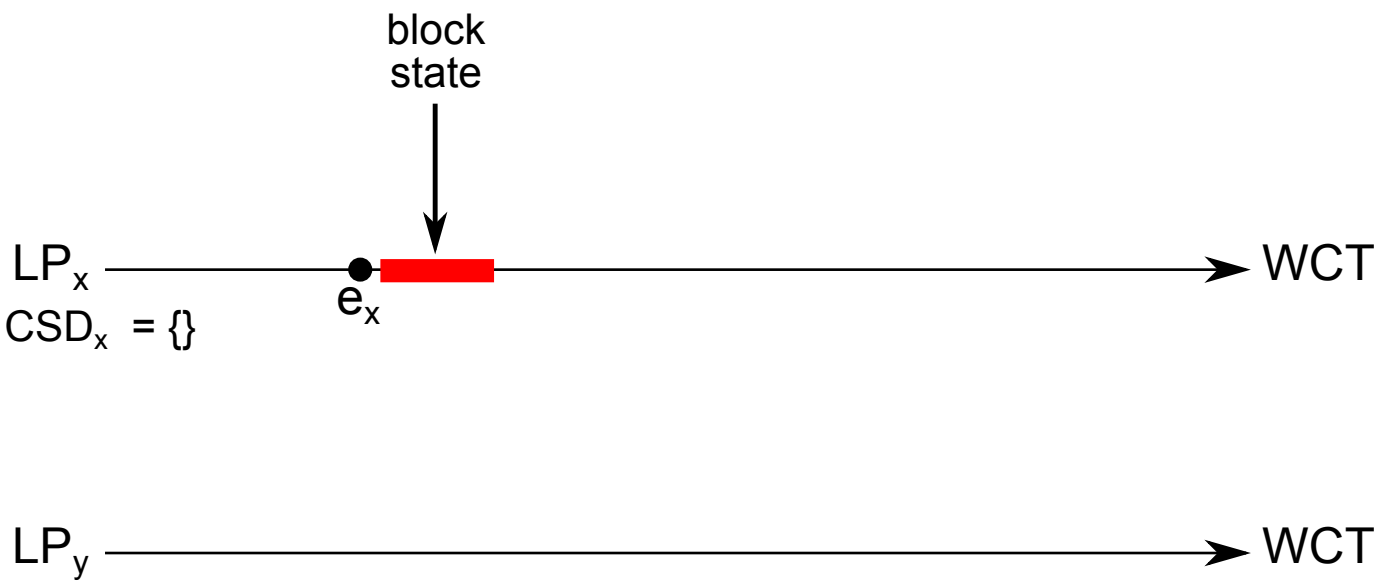

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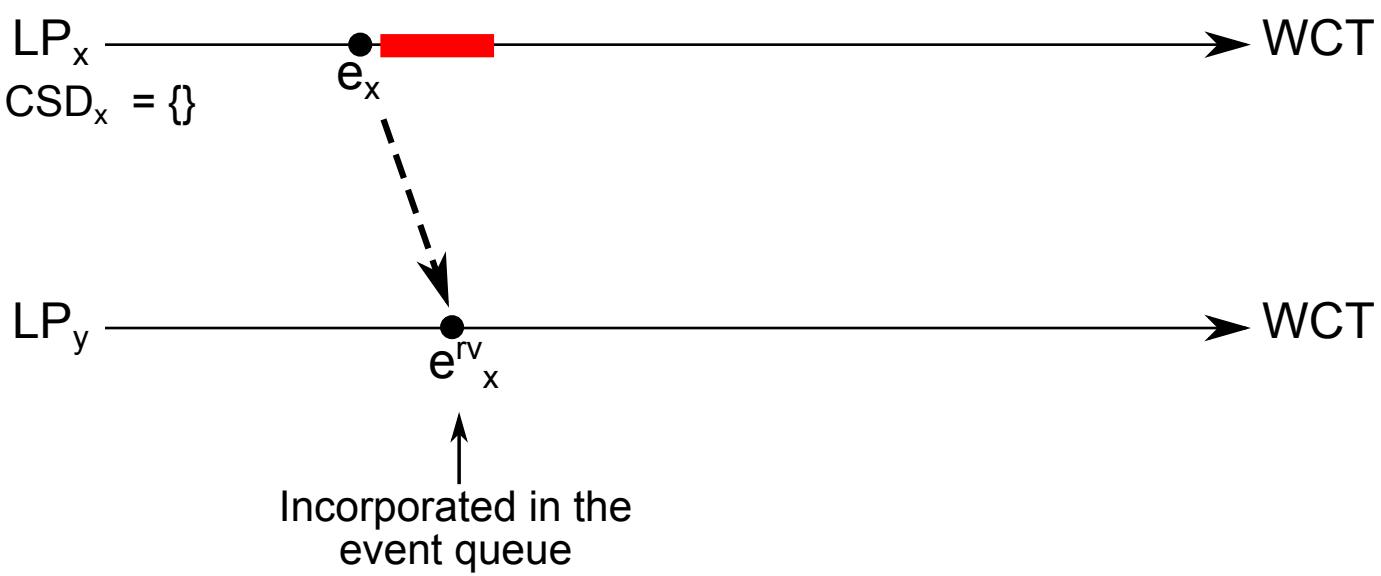

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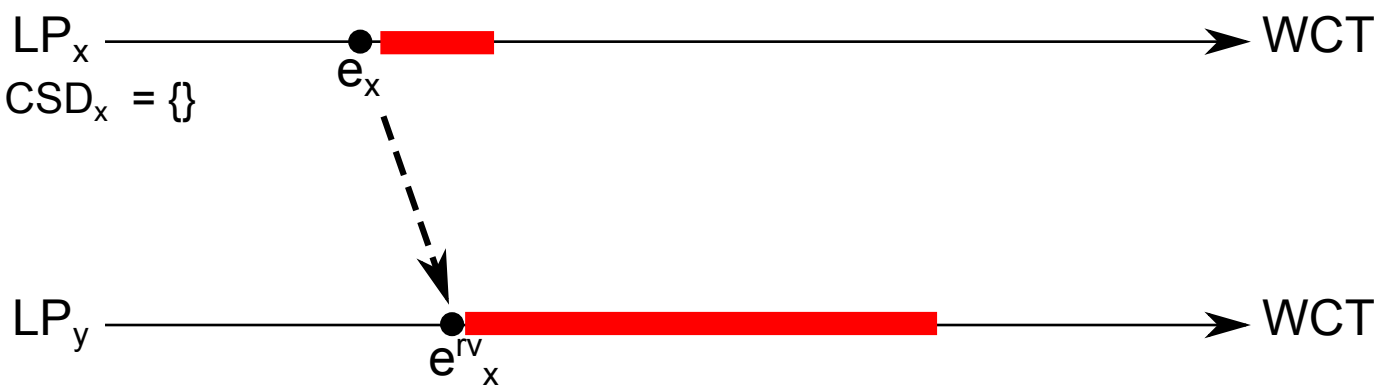

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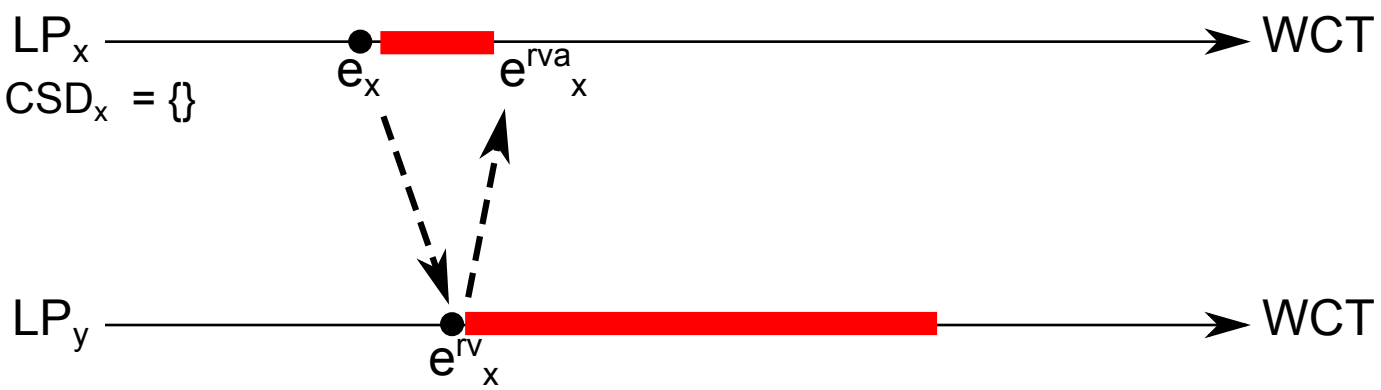

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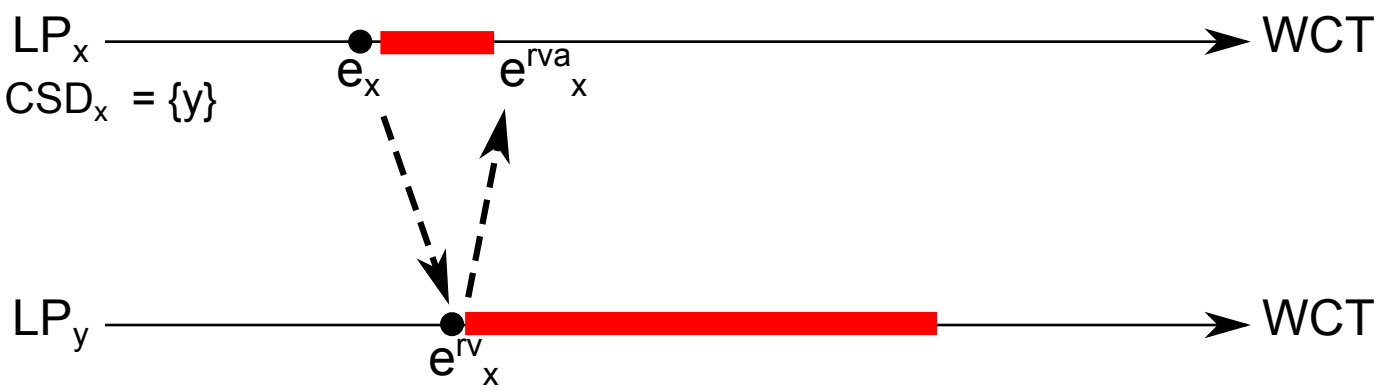

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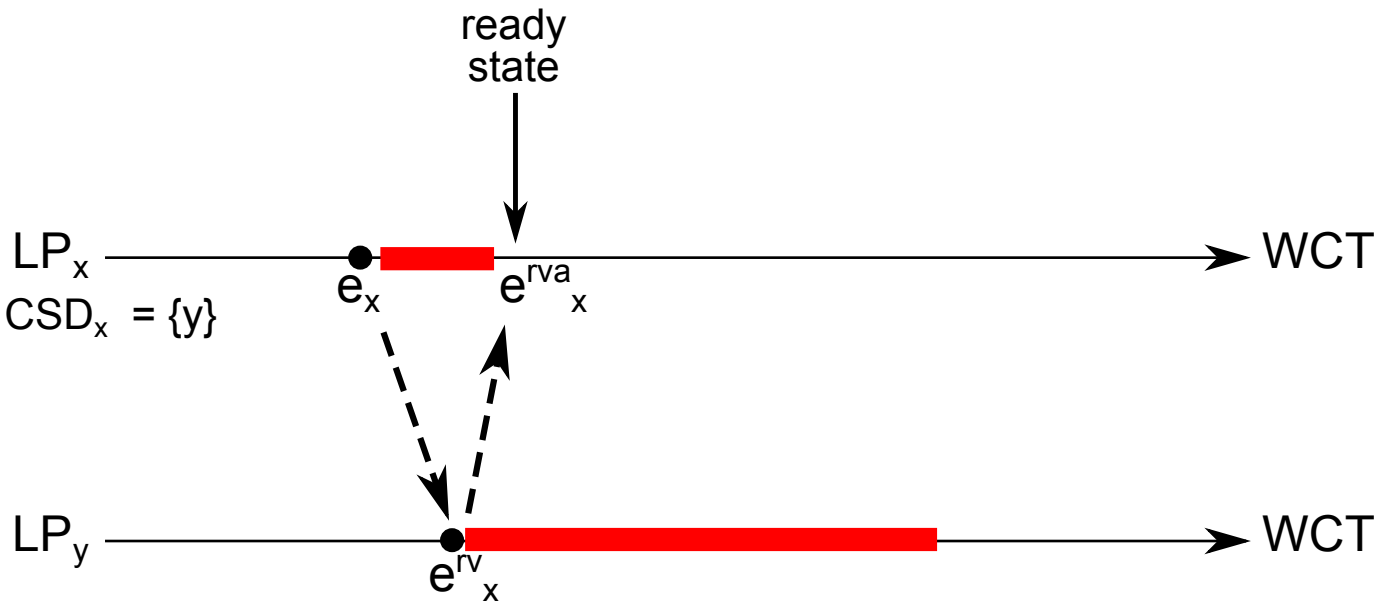

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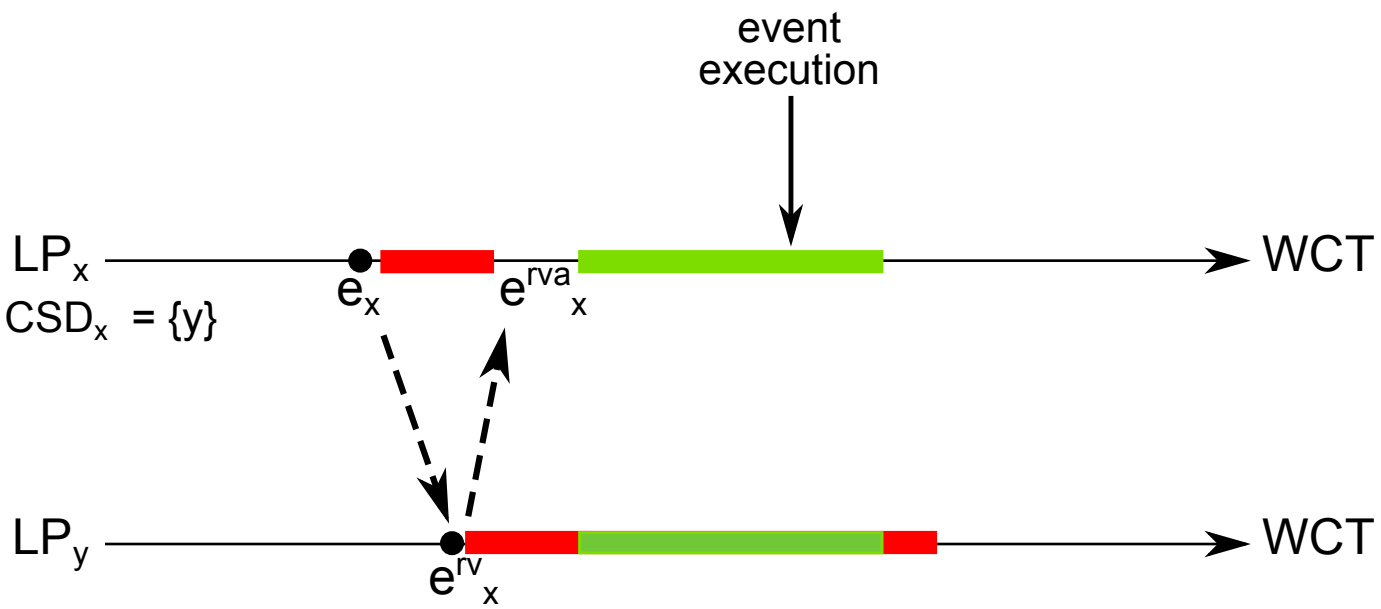

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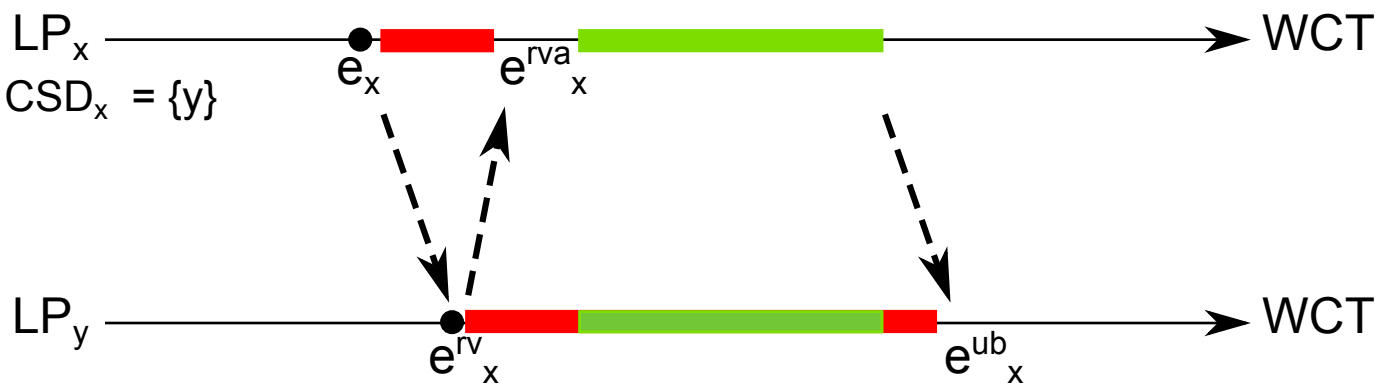

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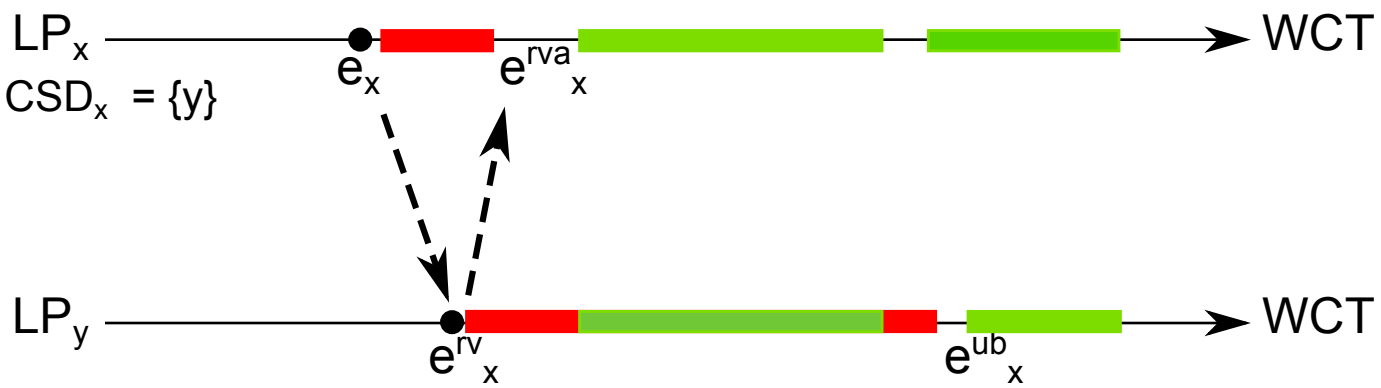
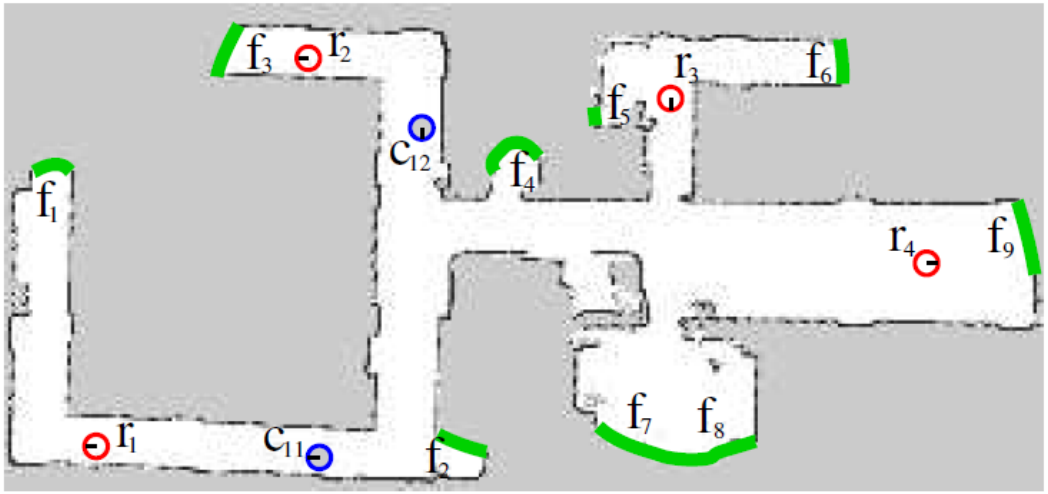


Programmability and Performance Study: Distributed Multi-Robot Exploration and Mapping



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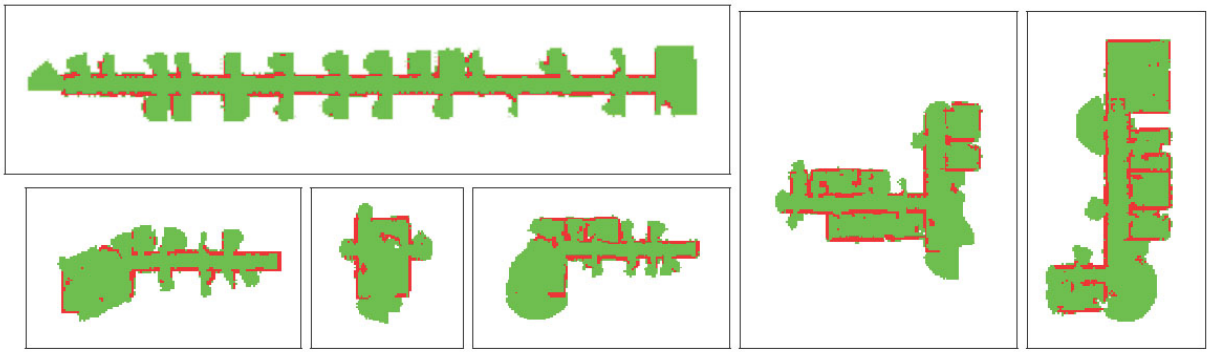
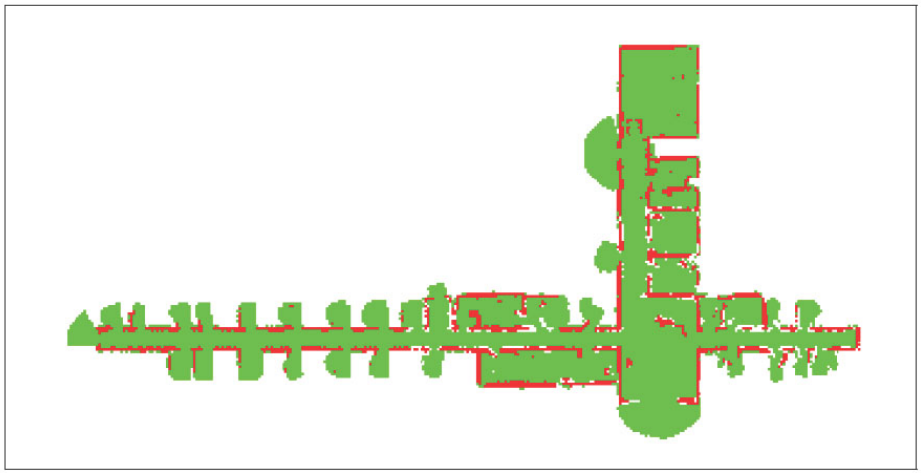


(a) input maps



(b) merged map

Programmability and Performance Study: Distributed Multi-Robot Exploration and Mapping

- The map is constructed online
- Robots explore independently, until they accidentally meet:
  1. they use their sensors to estimate their mutual physical position
  2. they create a rendez-vous point to verify the estimation's goodness
  3. if the hypothesis is verified, they exchange the so-far acquired data
  4. they form a cluster
- Clusters allow to explore collaboratively:
  - jointly define the next targets (reduce mapping time)
  - make a guess on the position of other robots (enlarge the cluster)

PDES Implementation Problems

- Discovering the presence of a nearby robots (number of exchanged messages)
- Estimating the respective position of the agents (many messages with the same timestamp)
- Exchanging data map information (non-negligible size)

- To solve these problems, the modeler must reason about optimistic synchronization and LPs' state separation: **no trasparency**

Using ECS: Initialization of Cells

```
1  // Allocated state
2  state = malloc(sizeof(agent_state_type));
3
4  <initialize the map>
5
6  // Allocate the presence bitmap
7  state->agents = malloc(BITMAP_SIZE(num_agents));
8  bzero(state->agents, BITMAP_SIZE(num_agents));
9  // Register the state
10 states[me] = state;
```

Using ECS: Entering a Cell

```
1 state->current_cell = event_content->cell;
2
3 // Register the position of the robot in the cell
4 cell = (cell_state_type *)states[state->current_cell];
5 cell->present_agents++;
6 SET_BIT(cell->agents, me - num_cells);
```

Using ECS: Explore the Cell

```
1 // Mark the cell as explored and "discover" the surroundings
2 state->visit_map[state->current_cell].visited = true;
3 memcpy(&state->visit_map[state->current_cell].data, cell->data,
      sizeof(unsigned int) * 6);
4
5 // Is there any other robot in the cell?
6 if(cell->present_agents > 1) {
7     <scan the bitmap>
8 }
```

Using ECS: Exchange Data with Robots

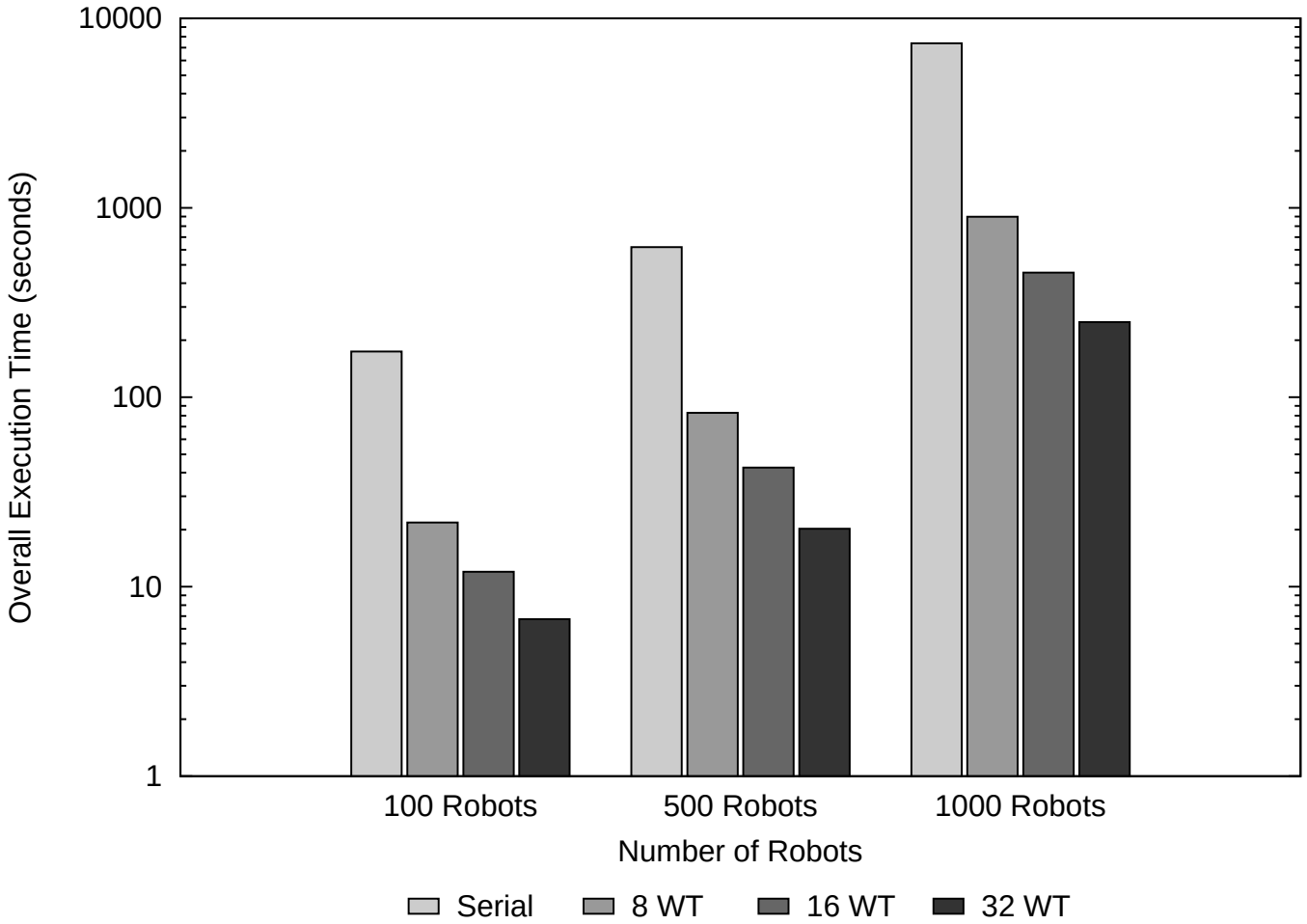
```
1 robot = (agent_state_type *)states[robot_index];
2 for(j = 0; j < num_cells; j++) {
3     if(robot->visit_map[j].visited) {
4         memcpy(&state->visit_map[j], &robot->visit_map[j], sizeof(
              map_t));
5     } else if (state->visit_map[j].visited) {
6         memcpy(&robot->visit_map[j], &state->visit_map[j], sizeof(
              map_t));
7     }
8 }
```

Performance Evaluation: Set up

- Hardware configuration:
  - HP ProLiant server equipped with 64GB of RAM
  - 4 8-cores CPU (32 cores total)

- Benchmark configuration:
  - 4096 cells
  - Variable number of robots: 100, 500, 1000
  - Serial simulation, vs Parallel Simulation using 8, 16, 32 cores

Performance Evaluation: Results



Thanks for your attention

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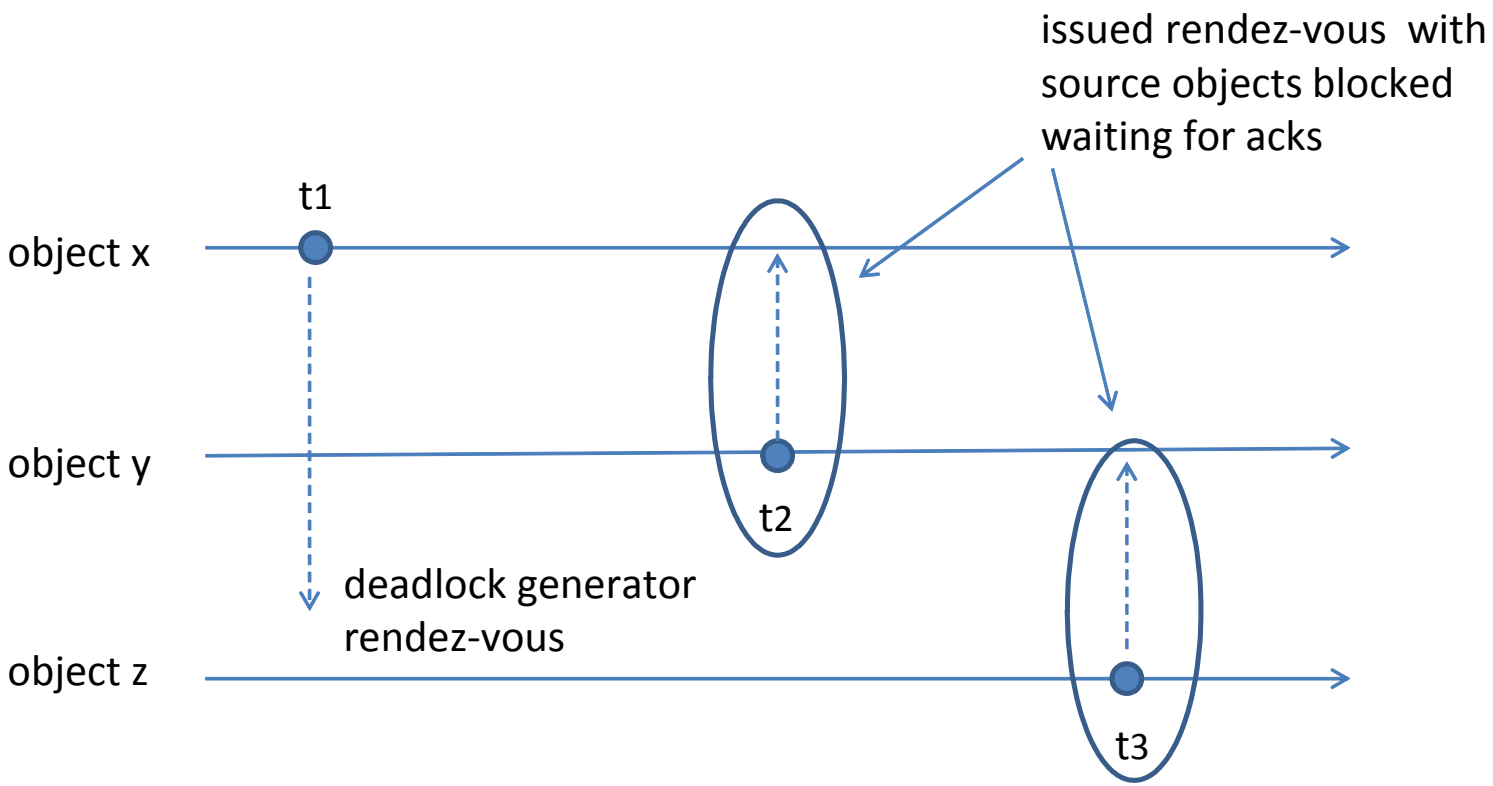
Rollback

- Rollback of LP_x is managed via traditional annihilation scheme
- Rollback of LP_y must be explicitly notified
  - A restart event e_x^{rvr} is sent to LP_x
- All other events are not incorporated in the queue
  - They do not require special care for rollback operations
  - They are simply discarded if no rendez-vous ID is found

Progress: Deadlock



Progress: Domino Effect