Model checking example: Scheduling of tasks

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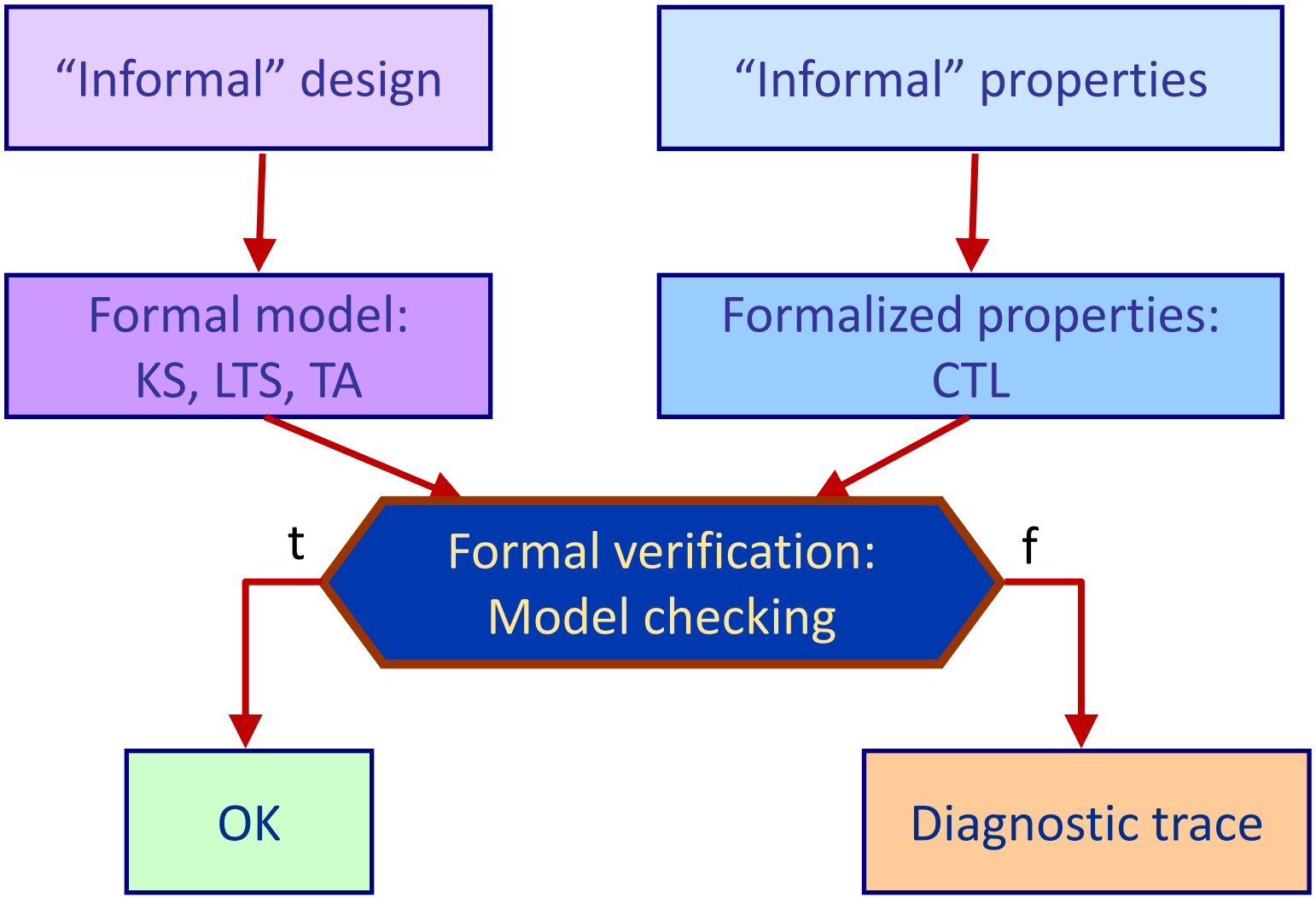
Formal verification: Goals

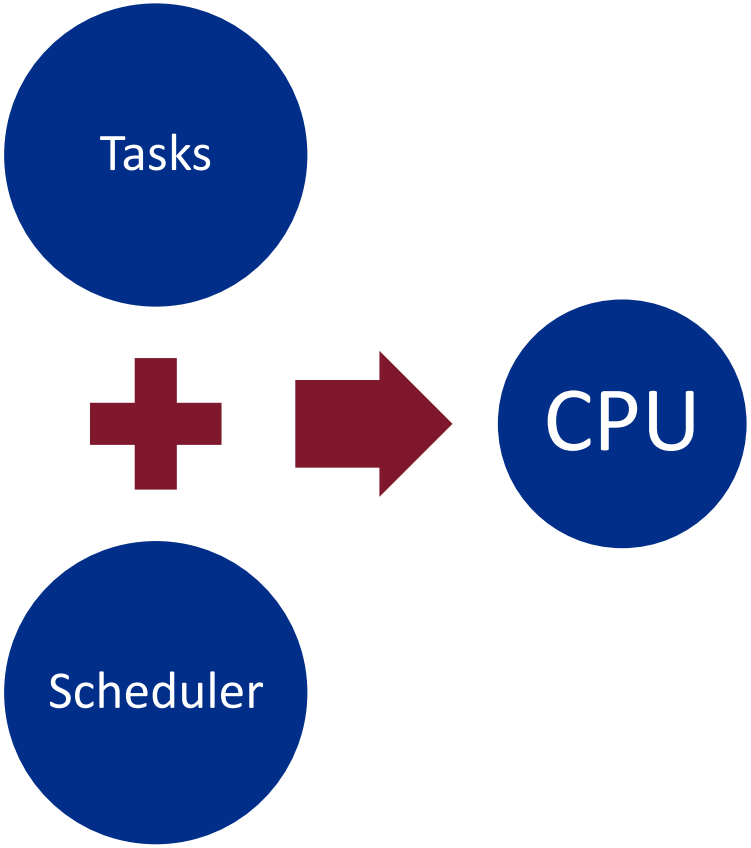


The problem

- Modeling tasks and threads in a simple operating system (OS)
  - Tasks are executed in fixed length periods
  - At the beginning of each period, tasks decide (non-deterministically) if they “apply” for running or if they decline running in that period
  - Each task requires a given percentage of CPU
  - Finite number of OS threads, one task per thread
  - At the end of a period, tasks are stopped and the OS returns to its initial state
  - The process above is repeated

The main components (1/2)

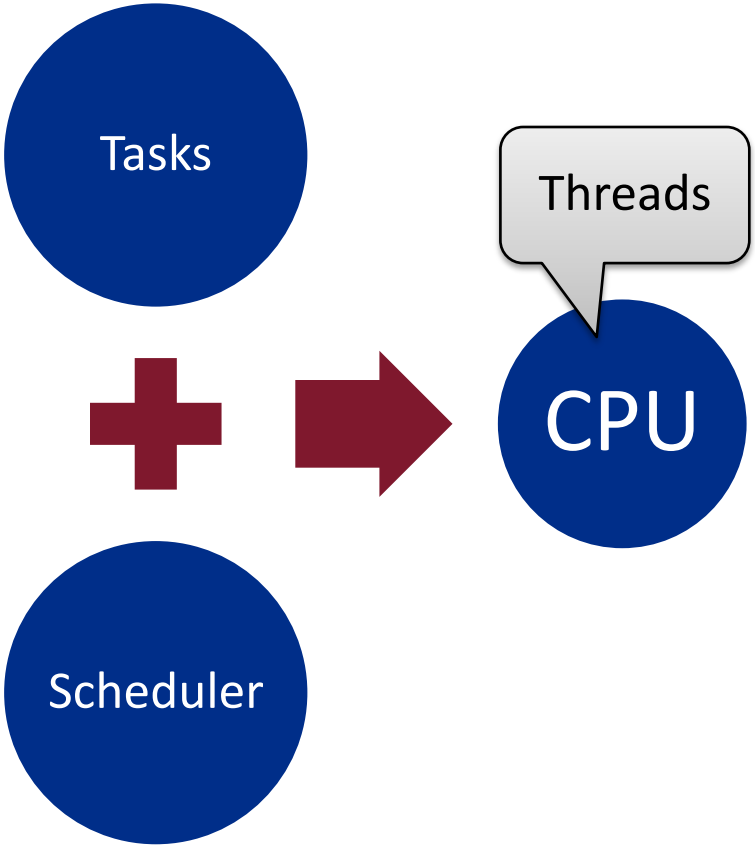
- Tasks
  - Affinity: probability that the task “applies” for running
  - Demand: the task requires (10*Demand) percent of CPU load
  - Priority: priority level of the task (higher number means lower priority)



- The total CPU load must be at most 100% for the tasks that are selected for running
- Within this limit, tasks have to be selected based on their priority

The main components (2/2)

- Scheduler
  - Selects running tasks from those that “applied” for running
  - There is a limited number of threads that can run tasks
  - Each task is allocated to a separate thread
  - No more tasks can be running than the number of threads
- CPU
  - Resource needed to run tasks
  - Two states: active, inactive
  - Tasks can run in active state
  - A preemptive interrupt can occur in active state

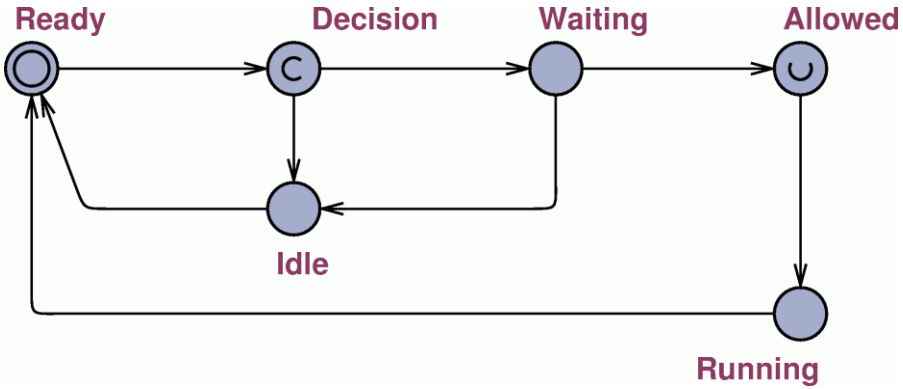


Basic operation of the system

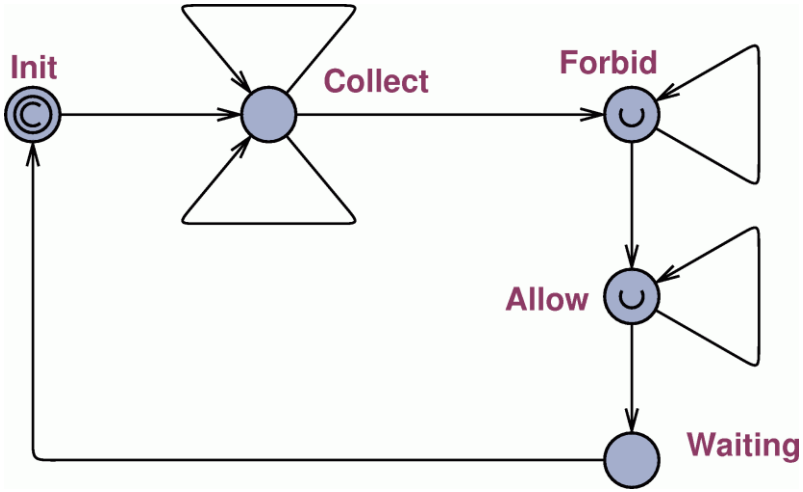
- The tasks
  - Generate a random number p between 0 and 10 when leaving their initial state
  - This is compared to their Affinity parameter:
    - if $p \geq$ Affinity, then they apply for running,
    - otherwise they decline to run and become inactive
- The scheduler
  - Collects applications from the tasks
  - Processes applications: orders the tasks descending by priority and CPU requirement, while observing the limits
  - Assigns the selected tasks to threads and stores this assignment in a global data structure

Let's start modeling!

- Task
  - Ready: initial state
  - Decision: decides on running
  - Idle: declined, inactive
  - Allowed: selected for running
  - Running: runs

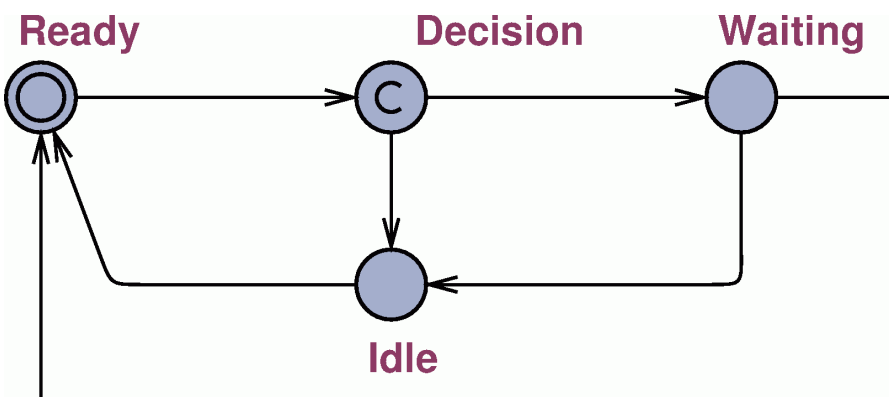


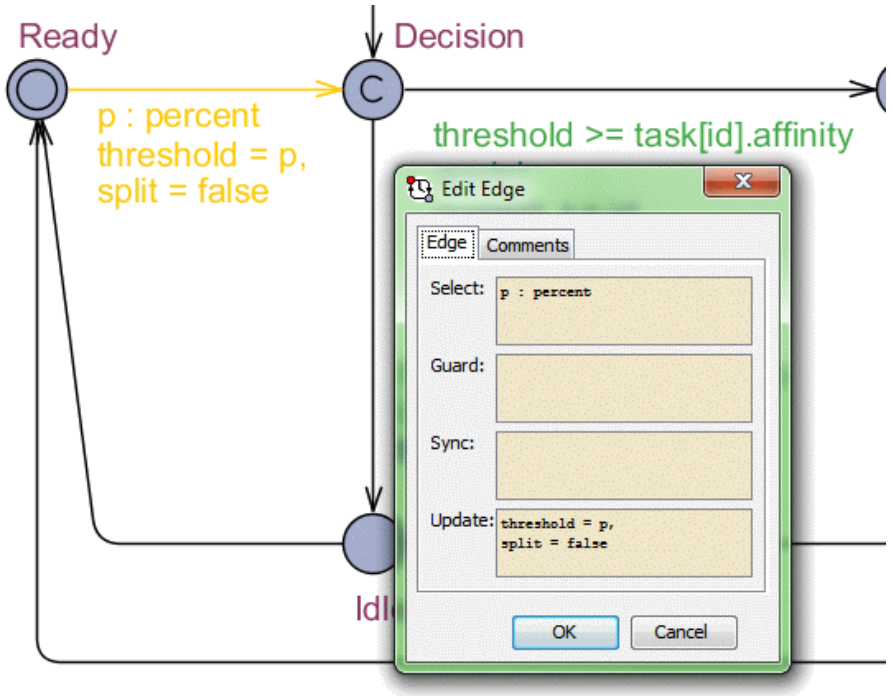
- Scheduler
  - Init: initial state
  - Collect: collects applications and declined statuses
  - Forbid: notifies rejected tasks
  - Allow: notifies selected tasks
  - Waiting: waiting to end period



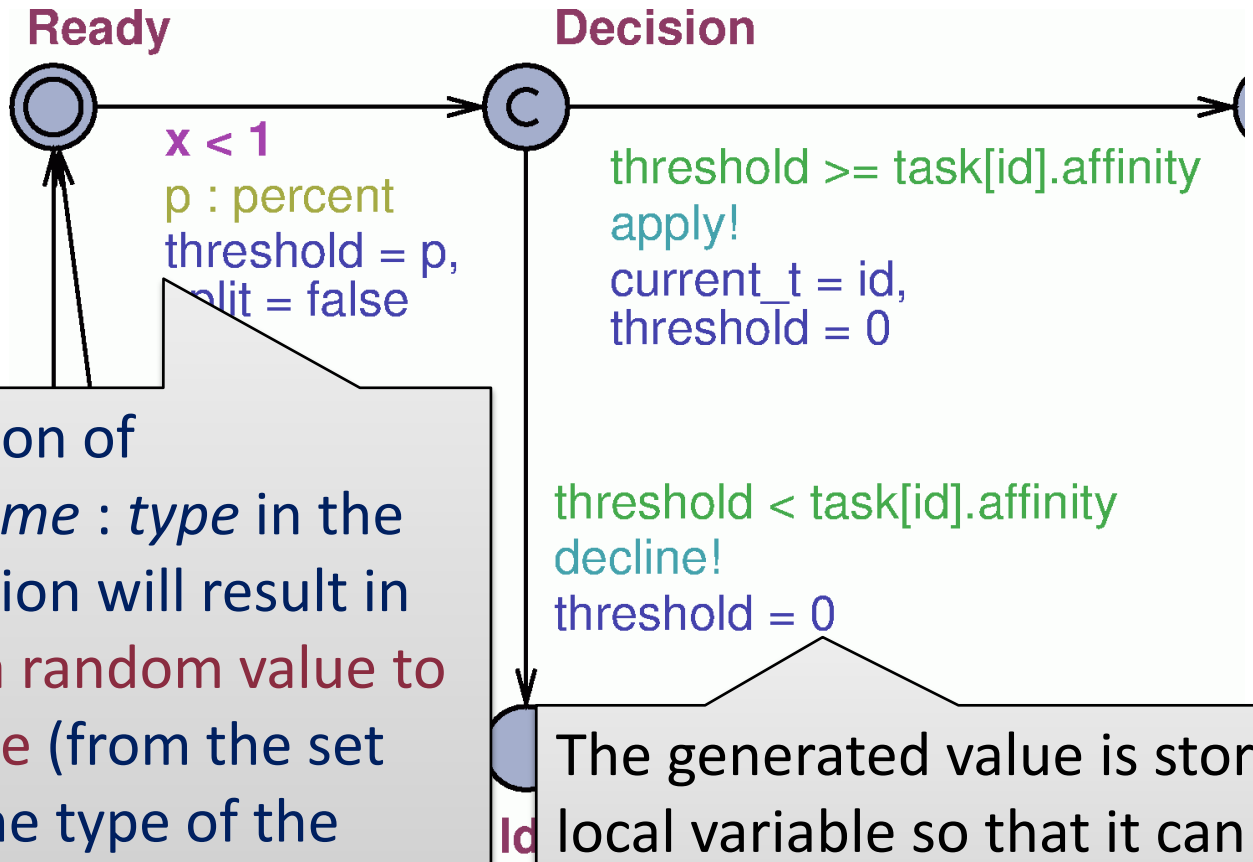
Modeling random choice: Alternatives

- Simple solution
  - UPPAAL chooses randomly from enabled transitions
  - Is it what we want? No, because probabilities should be proportional to the affinities
- Correct solution
  - Generate random value using Select construct of UPPAAL





Modeling random choice: The select construction



A declaration of *variablename* : *type* in the Select section will result in assigning a random value to the variable (from the set given by the type of the variable) when taking the transition.

This variable can only be used in other expressions of the same transition!

The generated value is stored in a local variable so that it can be used in the proceeding steps.

The purpose of the Committed state is that the two operations should not be interrupted.

Declarations

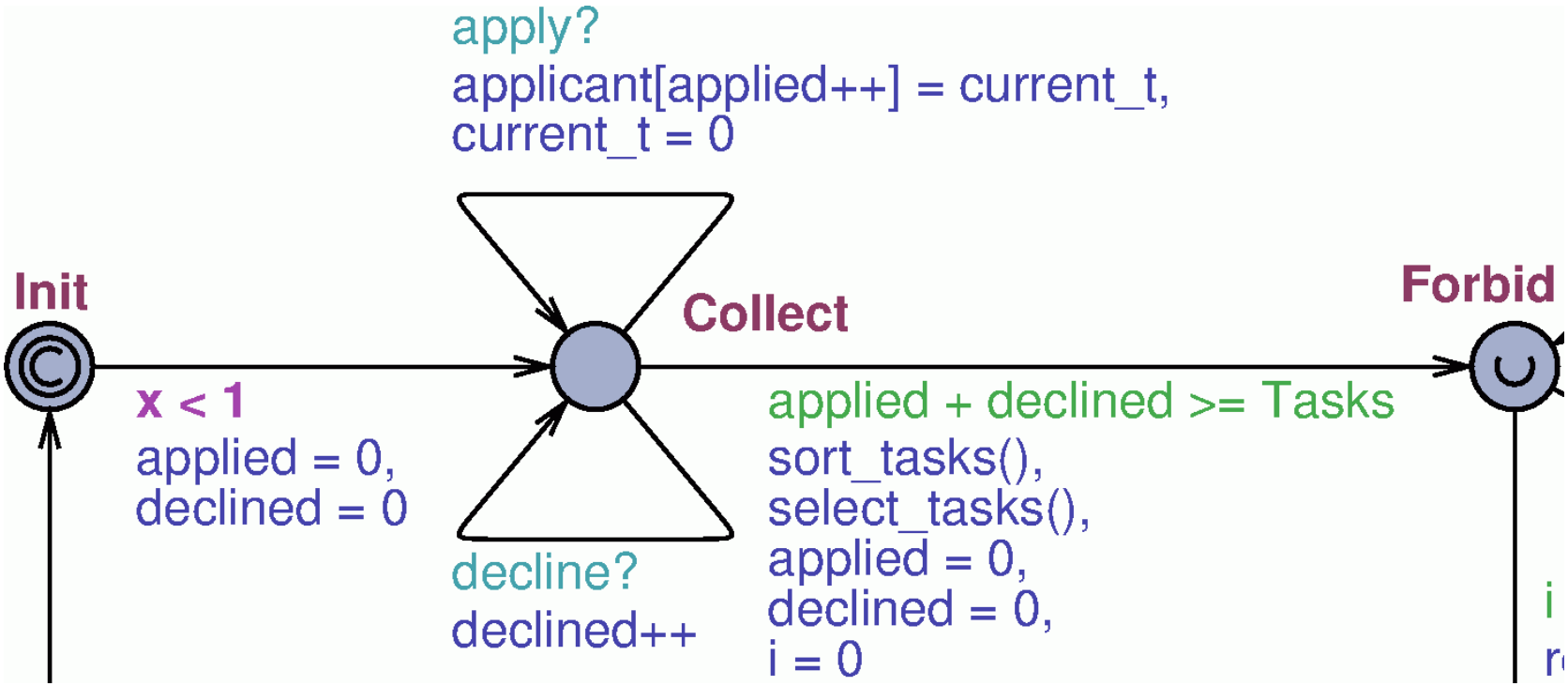
Global

```
typedef int[0,10] percent;

const int Levels = 3;
typedef int[0,Levels-1] p_level;

const int Tasks = 5;
typedef int[0,Tasks-1] t_id;
t_id current_t;

typedef struct {
  percent affinity;
  percent demand;
  p_level pri;
} task_t;

// affinity, demand, priority
const task_t task[Tasks] = {
…,
};
```

Local (Task)


```
clock x;
meta bool split = false;
percent threshold;
```

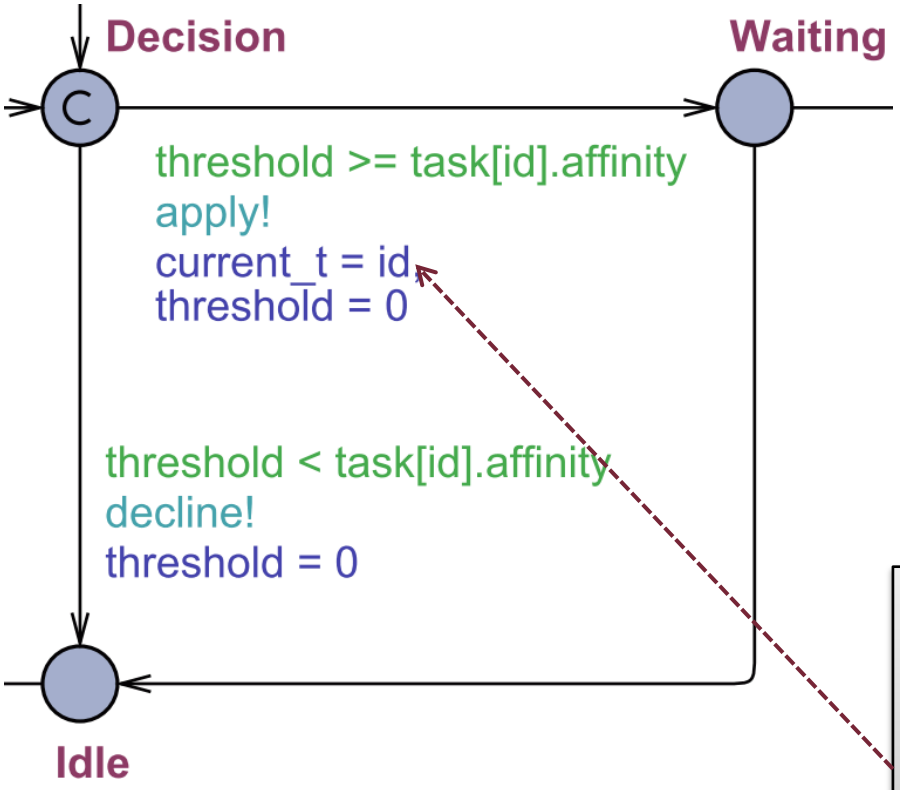
How does counting the tasks work?



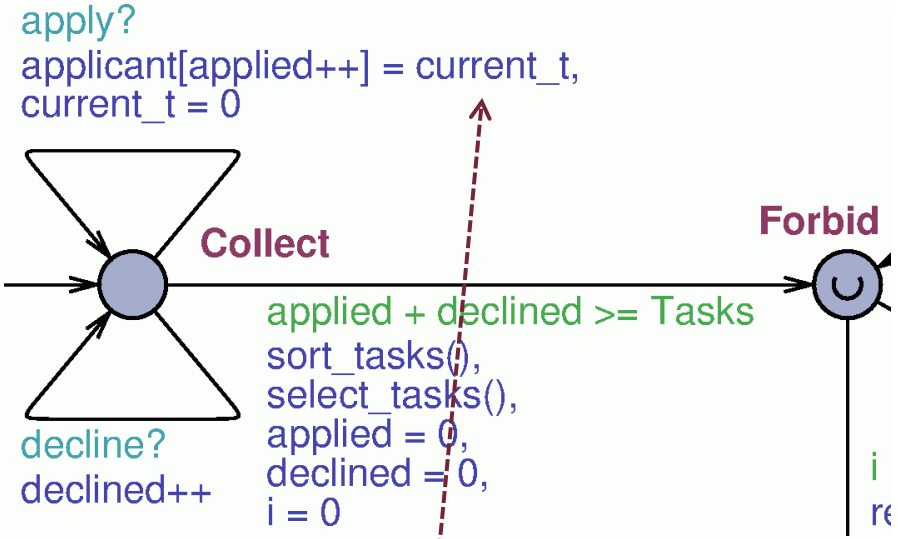
- We are staying in state Collect until each task either applied or declined
- Applied tasks are stored in a local array
- Functions sort_tasks() and select_tasks() are selecting tasks when entering the state Forbid

Collecting applied and declined tasks

Task



Scheduler

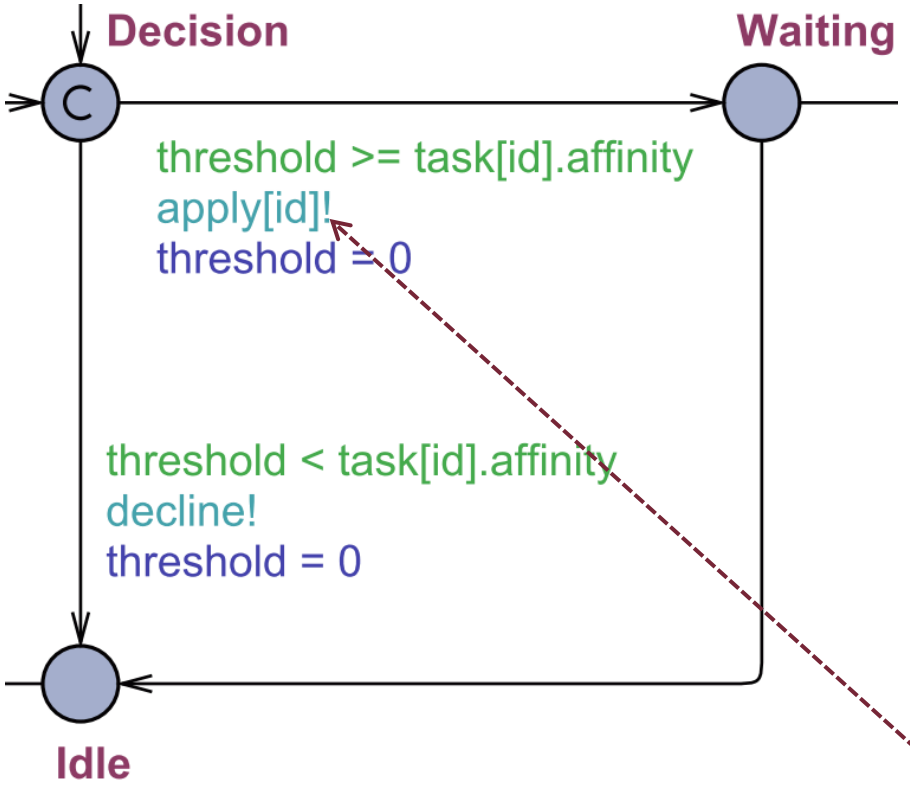


Using synchronous communication with a global variable.

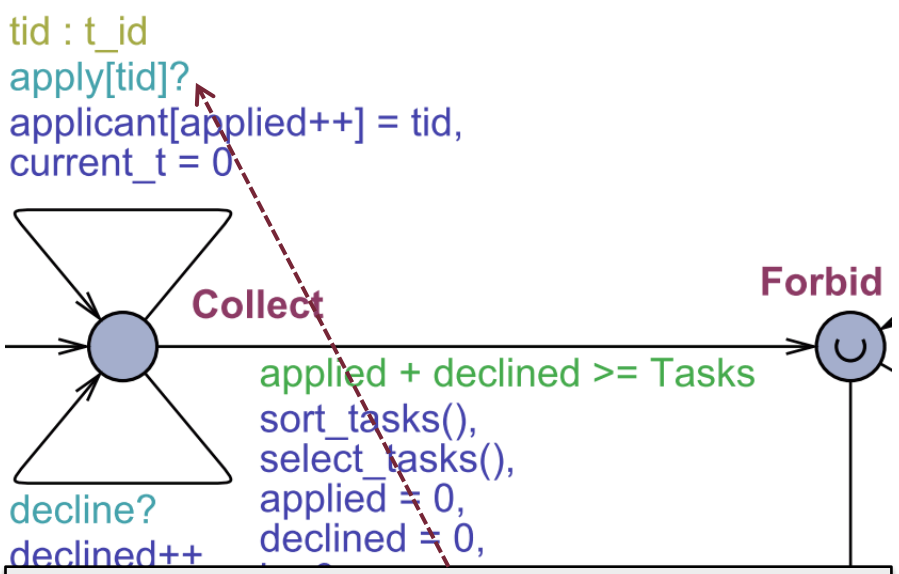
It is guaranteed that the Update of the sender is executed first!

Modeling synchronous communication

Task



Scheduler

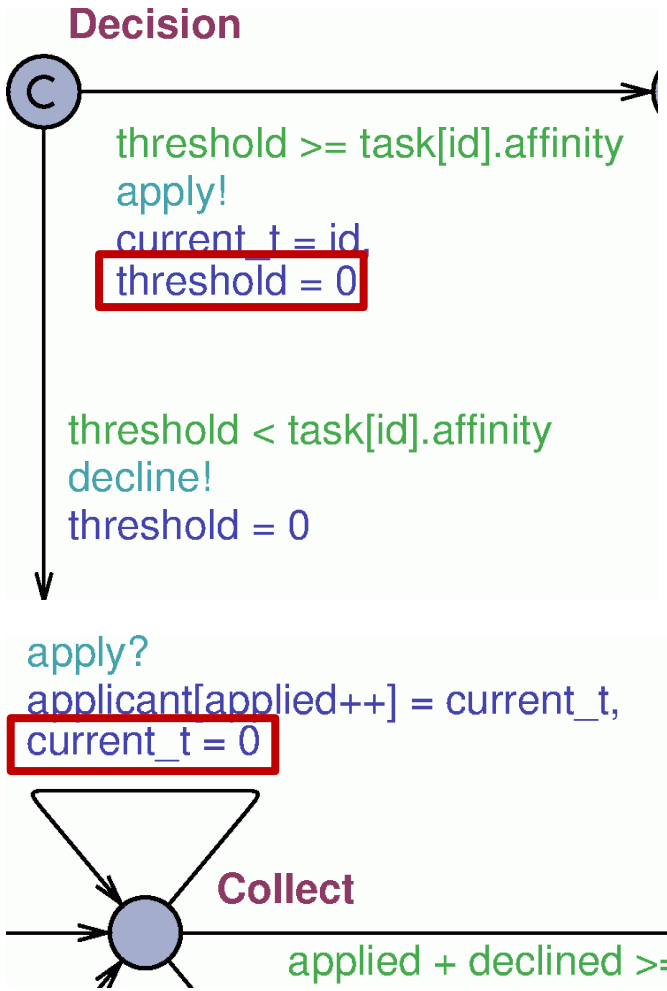


Modeling synchronous communication using an array of channels.

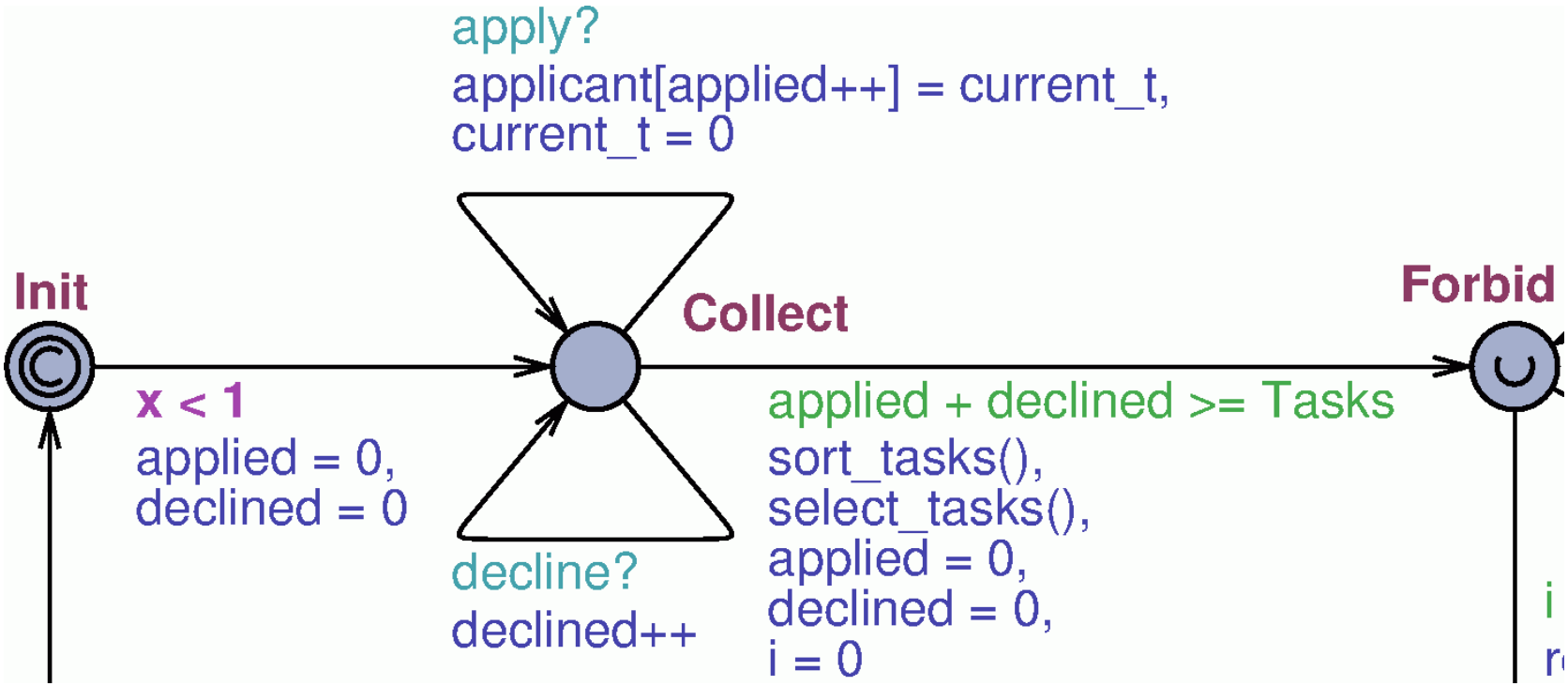
Can only be used for variables with small domain!

Why should we reset temporary variables?

- Temporary variable
  - In the state space: A set of trajectories for each value
  - Multiplies the size of the state space
  - Can be reduced by resetting the variable
- Interleaving
  - Transitions of concurrent automata in different orders
  - Same result on different paths
  - Can be reduced by synchronization and committed states



Let's get back to our model!



- Applied tasks are stored in a local array
- Functions sort_tasks() and select_tasks() are selecting tasks when entering the state Forbid
  - Ordering tasks decreasing by their priority and CPU requirement, while observing the limits

Selecting and rejecting tasks

- sort_tasks()
  - Uses a 2D array for ordering:

```
typedef struct {
  int[0,Tasks] length;
  t_id task[Tasks];
} buffer_t;
buffer_t buffer[Levels];
```

- select_tasks()
  - Collects selected tasks decreasing by priority until a limit is reached

- Let the parameters be:

```
// affinity, demand, priority
const task_t task[Tasks] = {
{0, 2, 0},
{3, 3, 1},
{3, 4, 1},
{3, 1, 1},
{3, 5, 2}
};
```

- Example applicants: 0, 2, 3, 4
- Example order:

```
buffer[0] = [0]
buffer[1] = [2, 3]
buffer[2] = [4]
```

- Selected: 0, 2, 3
- Rejected: 4

Ordering tasks based on CPU requirement

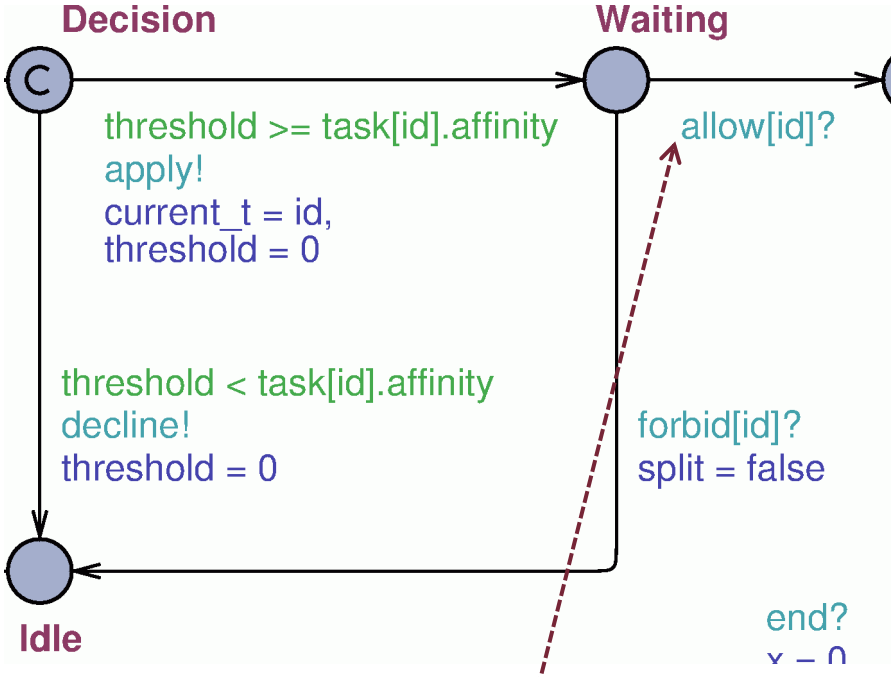
```
void insert_at(int[0,Tasks] pos, t_id tid) {
  int i;
  for (i = buffer.length; i > pos; i--) {
    buffer.task[i] = buffer.task[i - 1];
  }
  buffer.task[pos] = tid;
  buffer.length++;
}

void sort_tasks() {
  int i, j, pri, pos;
  for (i = 0; i < applied; i++) {
    pri = task[applicant[i]].pri;
    for (j = 0, pos = -1; j < buffer[pri].length && pos < 0; j++) {
      if (task[applicant[i]].demand > task[buffer[pri].task[j]].demand)
        pos = j;
    }
    insert_at(pri, pos < 0 ? buffer[pri].length : pos, applicant[i]);
    applicant[i] = 0;
  }
}
```

Selecting tasks while observing limits

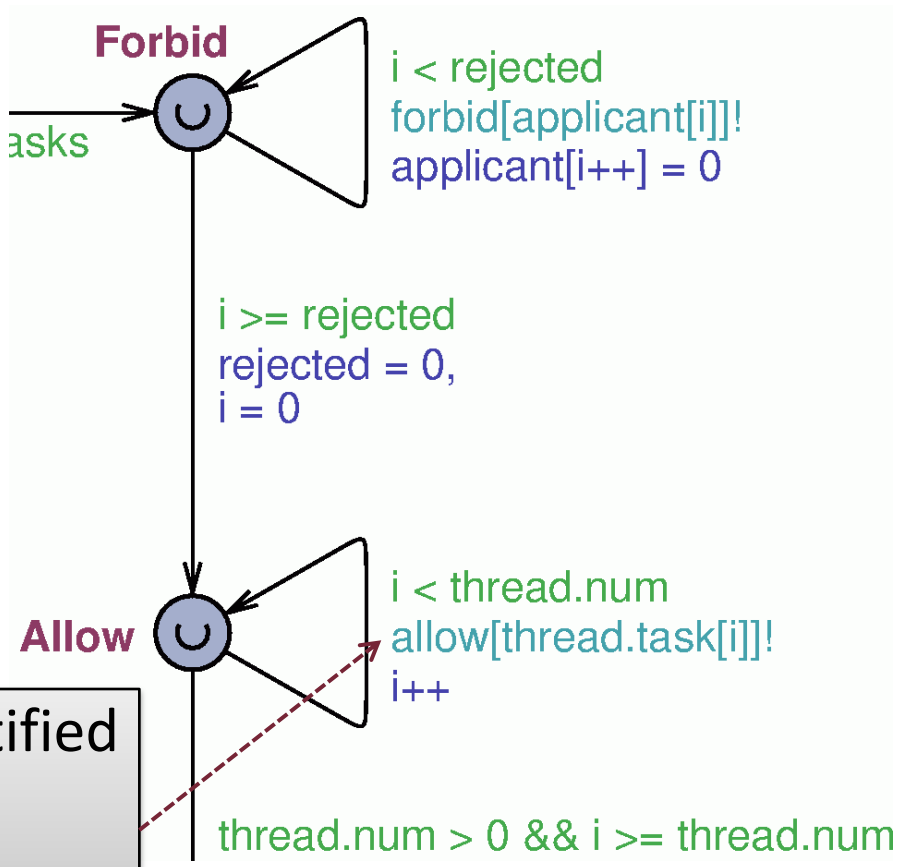
```
void select_tasks() {
  int i, pri;
  percent p = 0;
  rejected = 0;
  thread.num = 0;
  for (pri = 0; pri < Levels; pri++) {
    for (i = 0; i < buffer[pri].length; i++) {
      if (p + task[buffer[pri].task[i]].demand <= 10 &&
          thread.num < Threads) {
        thread.task[thread.num++] = buffer[pri].task[i];
        p = p + task[buffer[pri].task[i]].demand;
      }
      else applicant[rejected++] = buffer[pri].task[i];
      buffer[pri].task[i] = 0;
    }
    buffer[pri].length = 0;
  }
}
```

Notification about selection and rejection

Task



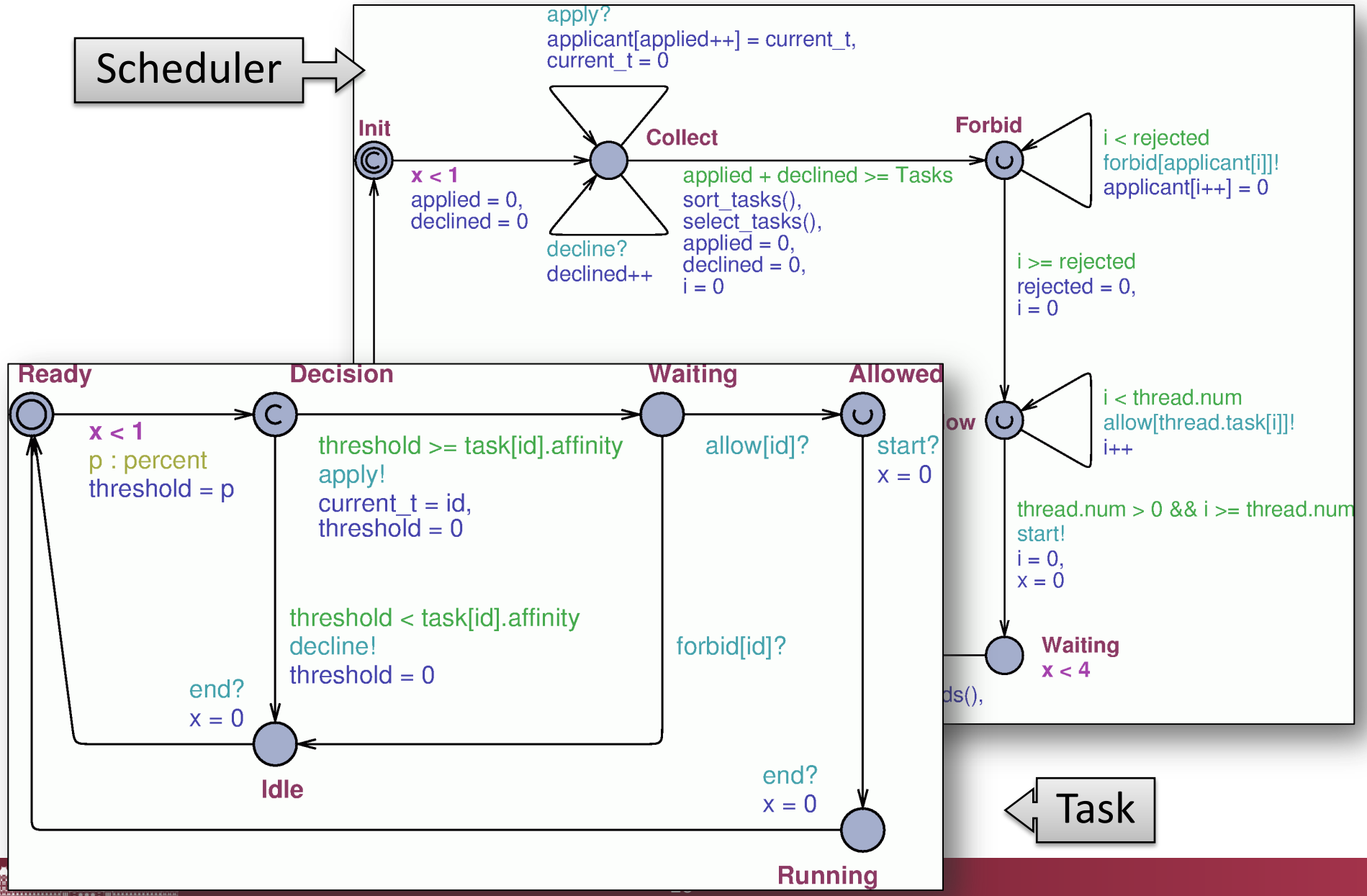
Scheduler



Selected and rejected tasks are notified individually on separate channels.

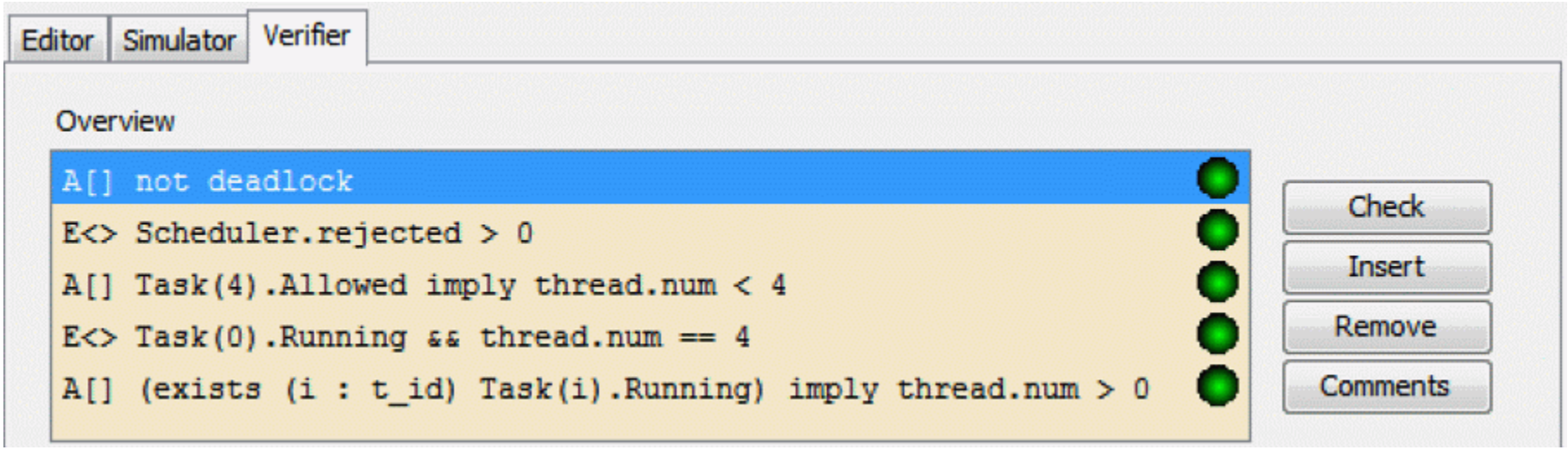
Temporary variables are reset.

The model already works (without a CPU)



Intermediate checking of the model

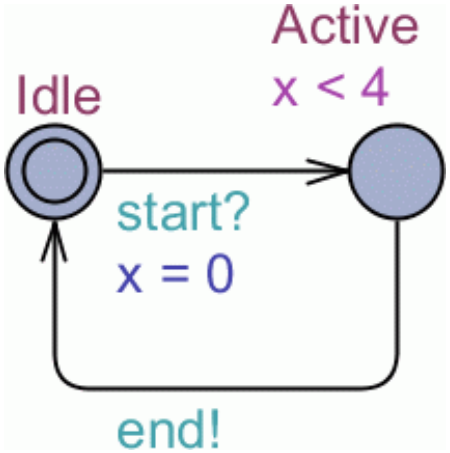
- We already have a functional system
  - It is recommended to check this intermediate system
- Some requirements:
  1. The system contains no deadlocks.
  2. It is possible that a task is rejected by the scheduler.
  3. When selecting task 4, not all threads can be occupied.
  4. It is possible that all threads are occupied.
  5. If a task is running then a thread is occupied.

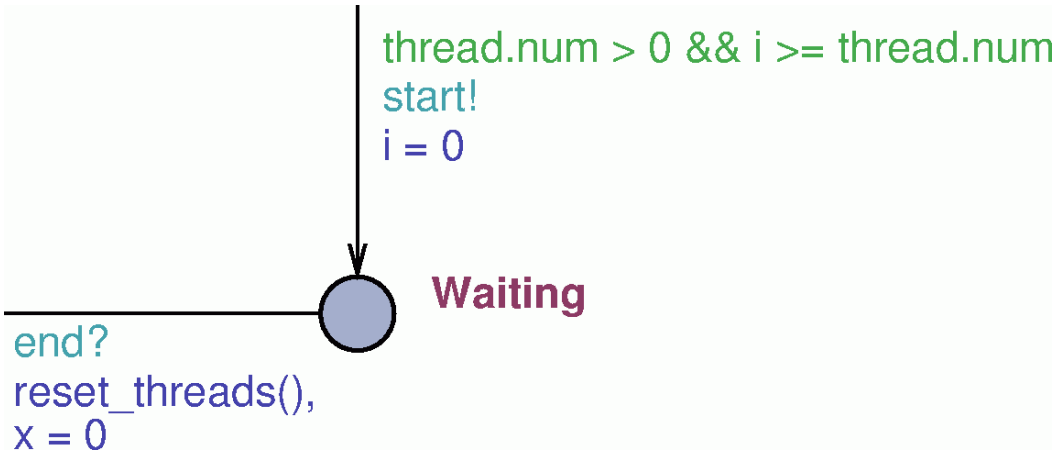


Extending the model with a CPU

- Starting signal is sent by the scheduler on a broadcast channel; after this:
  - Tasks selected to run change to running state
  - The scheduler changes to idle state until the end signal
  - The CPU changes to active state, threads and tasks running are stored in a global data structure
- The CPU sends an end signal when leaving active state; after this:
  - The CPU changes to inactive state
  - The scheduler changes to initial state, the list of running threads and tasks is cleared
  - Tasks also change to their initial state

Starting and stopping with CPU





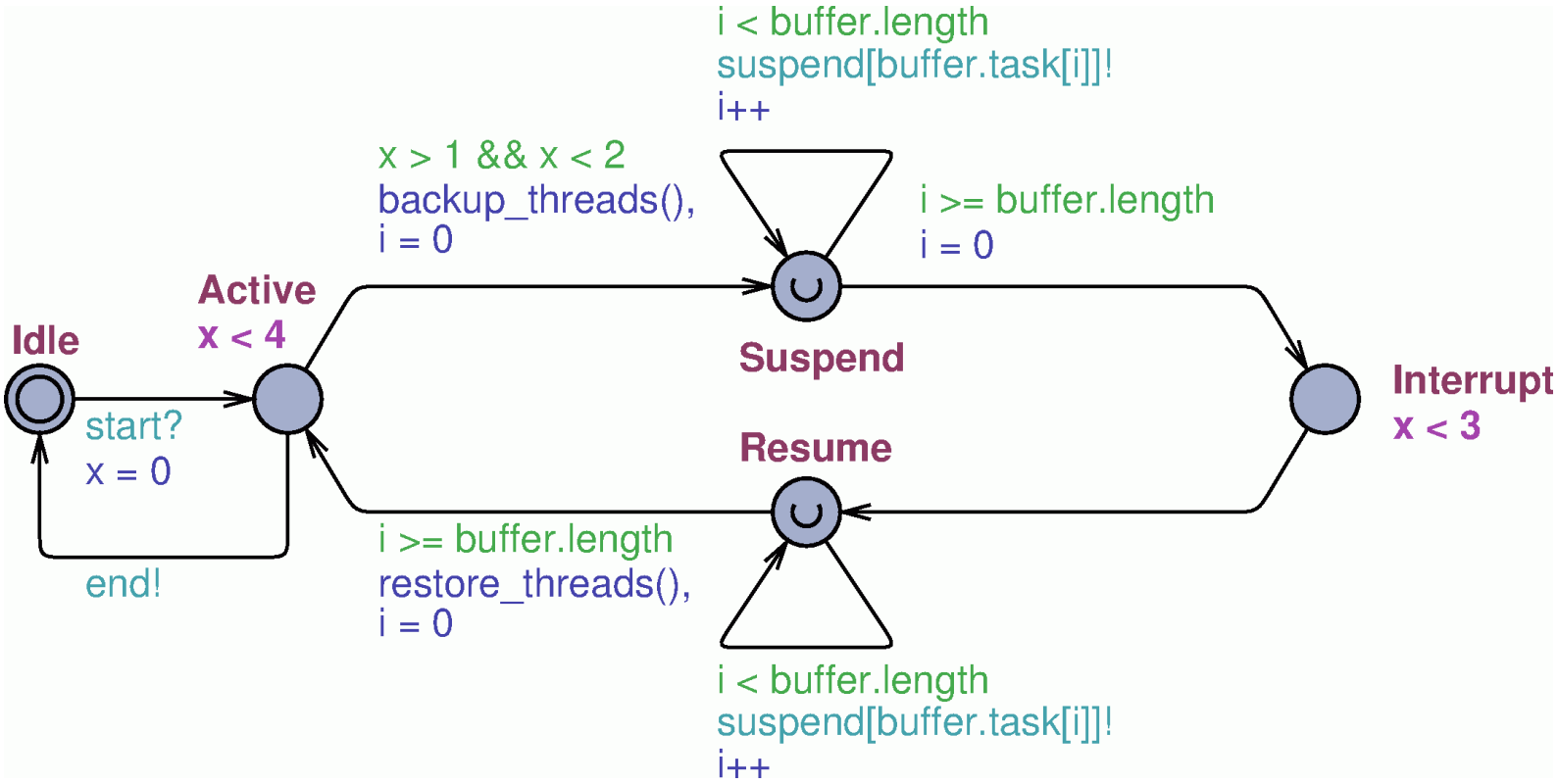

```
const int Threads = 4;

typedef struct {
  int[0,Threads] num;
  t_id task[Threads];
} thread_t;

thread_t thread;
```

```
chan apply, decline;
urgent chan allow[Tasks], forbid[Tasks];
chan suspend[Tasks];
broadcast chan start, end;

void reset_threads() {
  while (thread.num > 0)
    thread.task[thread.num-- - 1] = 0;
}
```

Let’s make the model more advanced: Interrupts!

- An interrupt can occur in the active state of the CPU
  - Certain tasks can be interrupted (preemptive)
  - CPU requirement of the interrupt determines which tasks will be interrupted
  - At least as many tasks must be suspended (starting with the lowest priorities), that result in enough CPU capacity available for the interrupt (the CPU requirements of the interrupt and the remaining tasks must be at most 100%)
    - The CPU selects the tasks to be suspended
    - It also notifies the suspended tasks
    - These tasks change to suspended state
  - After the interrupt
    - The CPU notifies the previously interrupted tasks
    - These tasks change to running state
    - The CPU also changes to running state

Modeling an interrupt



- Tasks are suspended by function backup_threads(), and restored by function restore_threads()
- Tasks are notified individually on separate channels about suspending and restoring

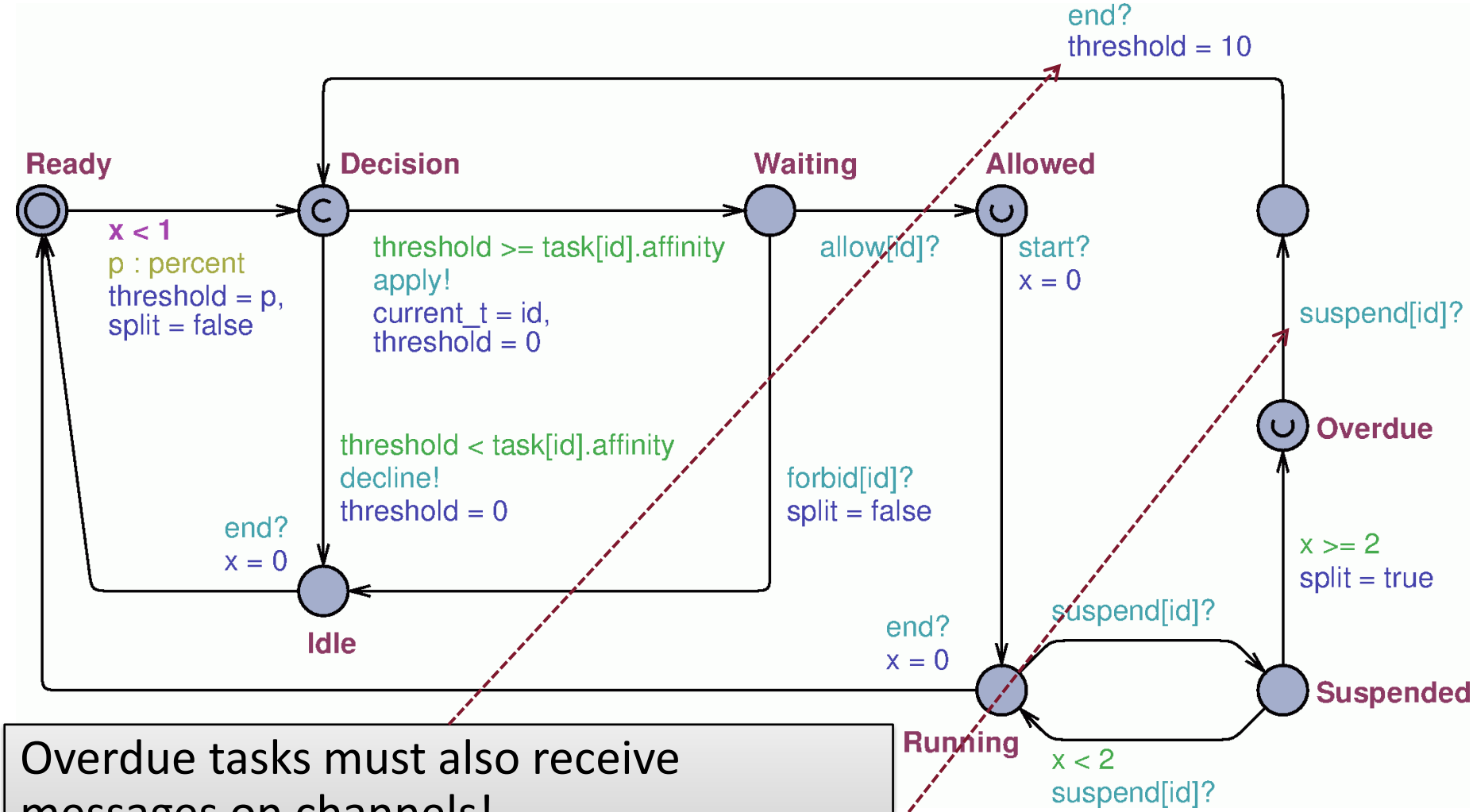
Selecting tasks for suspending

```
void backup_threads() {
  int i, p;
  t_id tid;
  for (i = 0, p = 0; i < thread.num; i++)
    p += task[thread.task[i]].demand;
  buffer.length = 0;
  for (i = 0; i < thread.num; i++) {
    if (p + i_demand > 10) {
      tid = thread.task[thread.num - i - 1];
      buffer.task[buffer.length++] = tid;
      thread.task[thread.num - i - 1] = 0;
      p -= task[tid].demand;
    }
  }
  thread.num -= buffer.length;
}
```

Even more advanced: Overdue tasks

- When tasks are suspended for too long, they will be overdue and they cannot be completed in the current period
- Such overdue tasks will try to continue running in the next period
- This is modeled by moving to the state where they apply for running (after the end signal)
  - I.e., they skip the random choice of applying or declining

Extending the model of a task with overdue

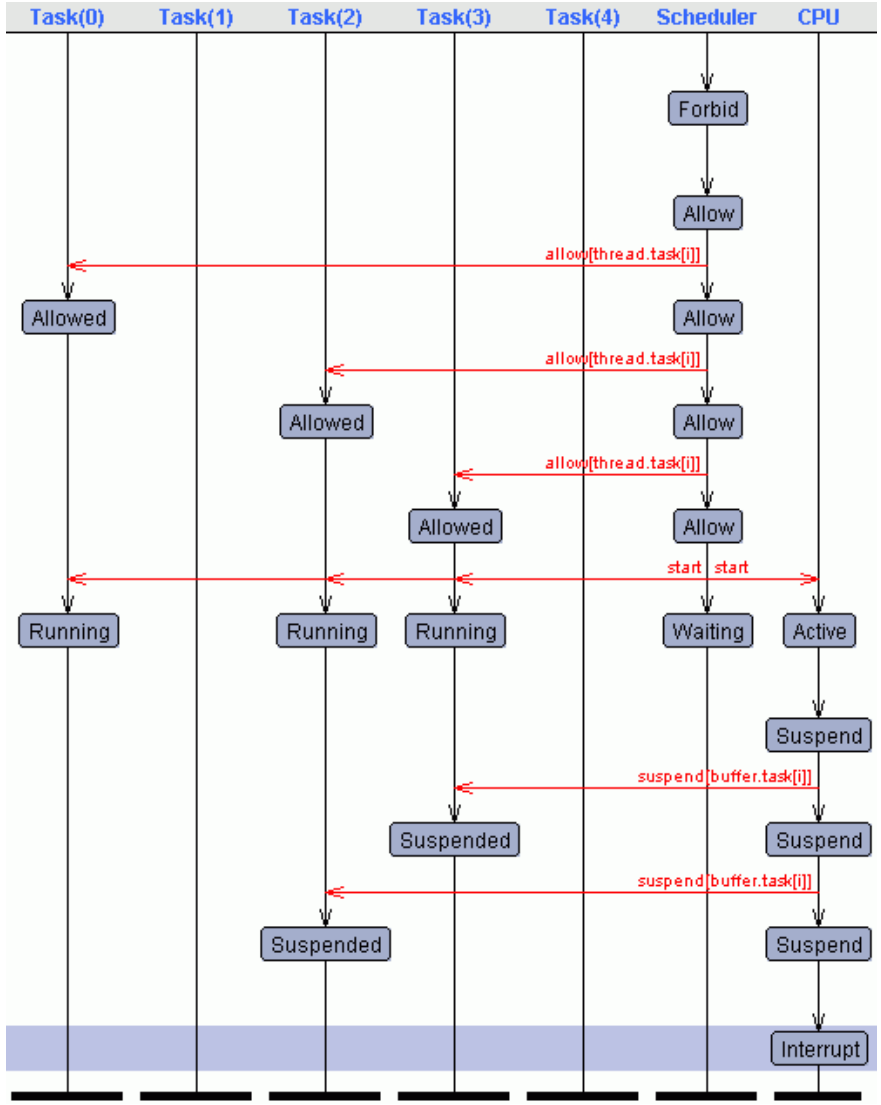


Overdue tasks must also receive messages on channels!

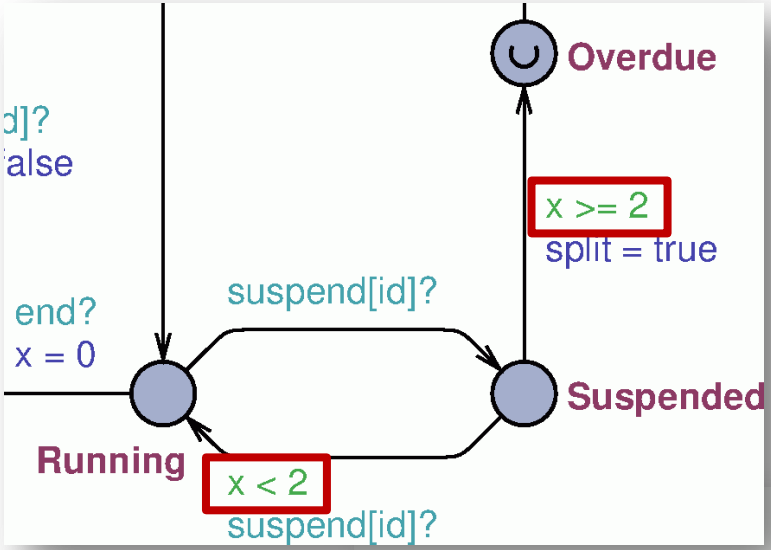
A value of 10 ensures application

We must introduce time limits

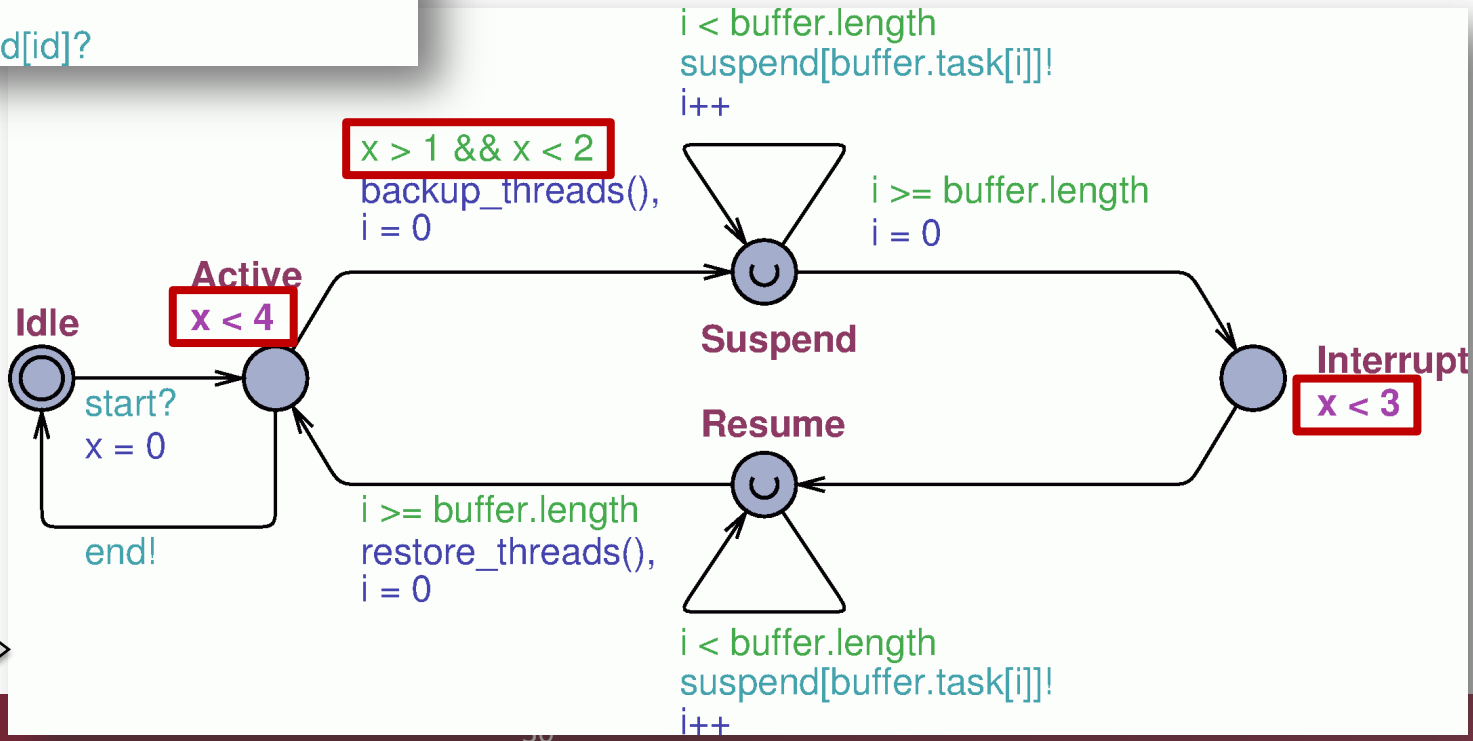
- A task has the following time limits
  - Clocks of the selected tasks, the scheduler and the CPU start at the same time
  - The CPU can be active for at most 4 time units
  - An interrupt can occur between the 1st and 2nd time units
  - The interrupt must last at most until the 3rd time unit
  - Suspended tasks become overdue after the 2nd time unit



Time limits in the model

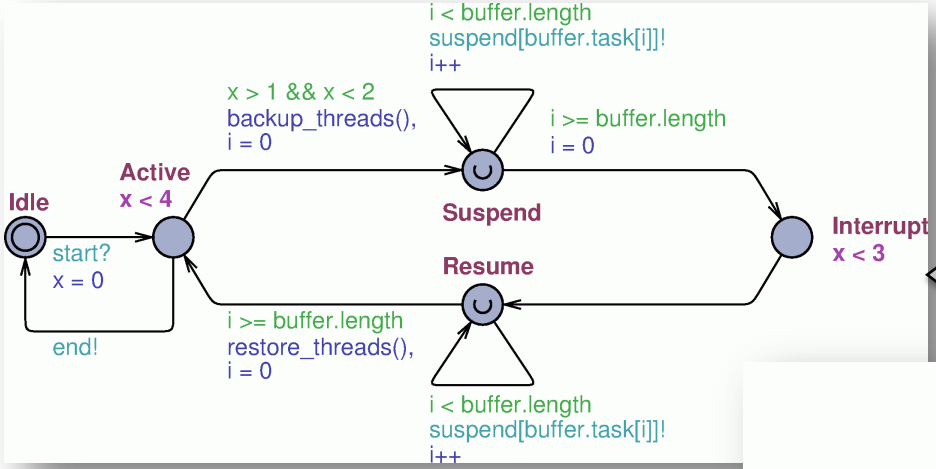


Task



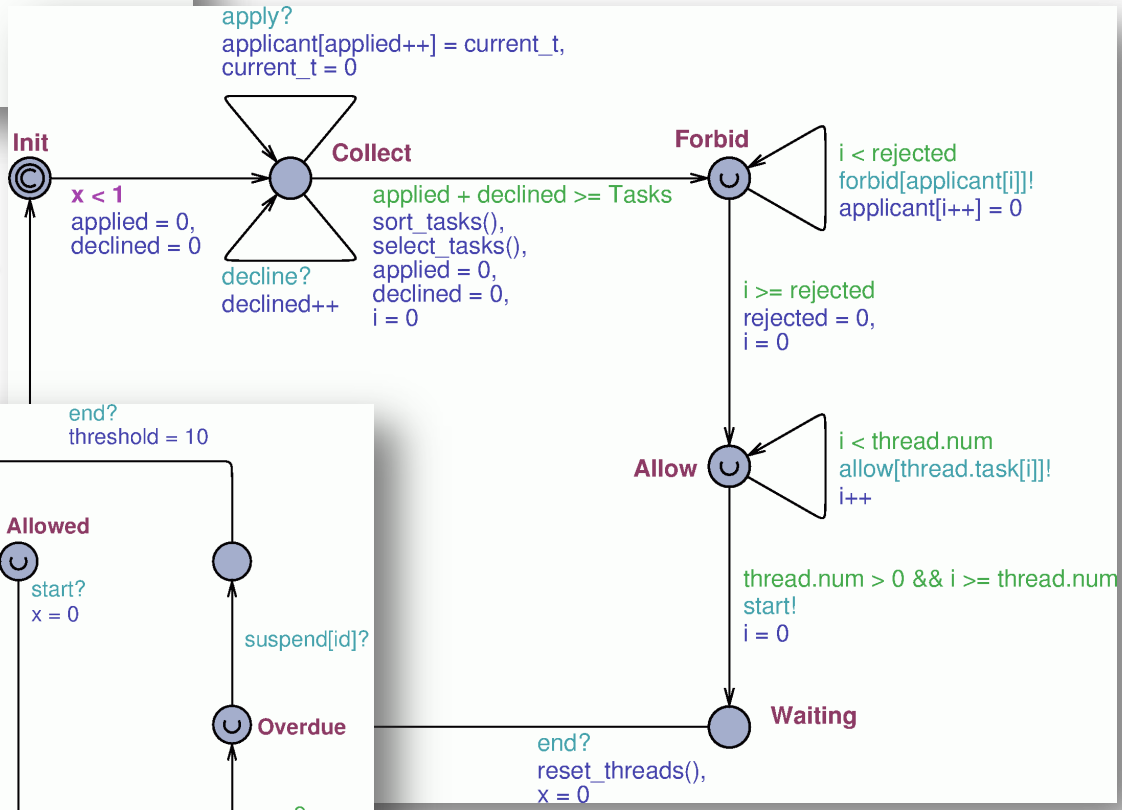
CPU

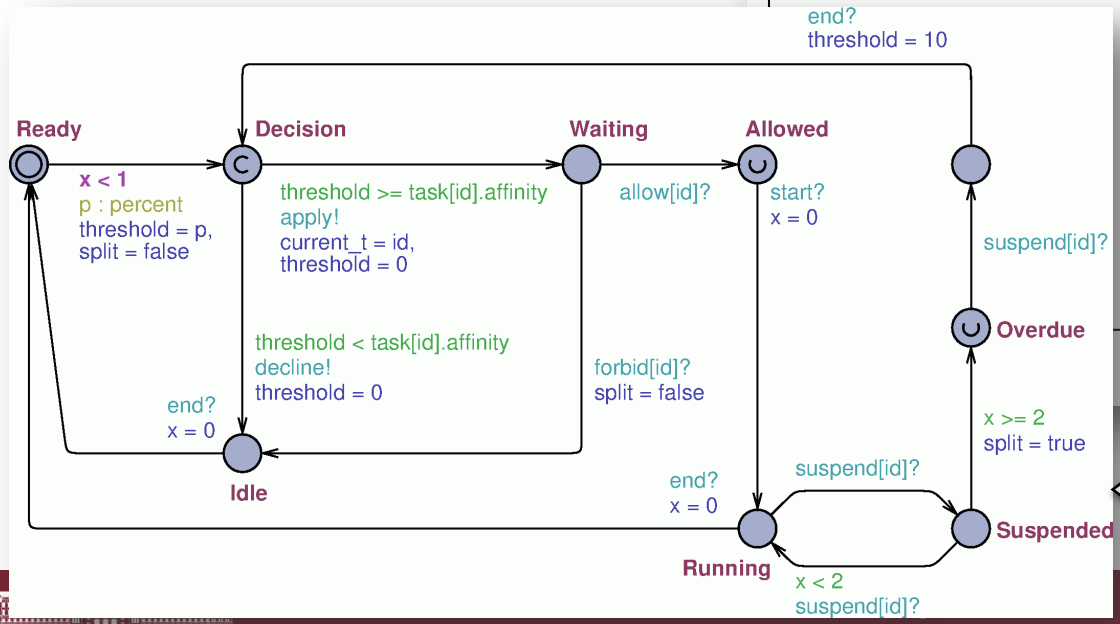
We are done!



CPU

Scheduler





Task

Requirements to be verified

1. The model is deadlock free.
2. It is possible that an applied task has to be rejected.
3. It is possible that all threads are busy, i.e., maximal number of tasks are running.
4. If a task is running, the number of busy threads in the global data structure is greater than 0.
5. It is possible that the CPU suspends more than 2 threads due to an interrupt.
6. There is an execution path where no task is suspended in all of the periods, but it is not possible for all paths, i.e., there is at least one path where at least one task is suspended at least once.
7. It is not possible that a task is in suspended state after the 3rd time unit.
8. If a task is suspended, it may be completed eventually.

Temporal logic expressions verified

Overview

1.	`A[] not deadlock`	●
2.	`E<> Scheduler.rejected > 0`	●
	`A[] Task(4).Allowed imply thread.num < 4`	●
3.	`E<> CPU.Active && thread.num == 4`	●
	`E<> CPU.Interrupt && CPU.buffer.length > 1`	●
4.	`A[] (exists (i : t_id) Task(i).Running) imply thread.num > 0`	●
5.	`E<> CPU.Interrupt && CPU.buffer.length > 2`	●
6.	`E[] (forall (i : t_id) Task(i).split == false)`	●
	`A[] (forall (i : t_id) Task(i).split == false)`	●
7.	`E<> (exists (i : t_id) Task(i).Overdue && Task(i).x > 3)`	●
8.	`Task(1).Overdue --> Task(1).split == true`	●
	`E<> (exists (i : t_id) Task(i).Overdue && Task(i).split == true)`	●