Embedded Software Engineering

3 Unit Course, Spring 2002

EECS Department, UC Berkeley

Chapter 1: RTOS Concepts

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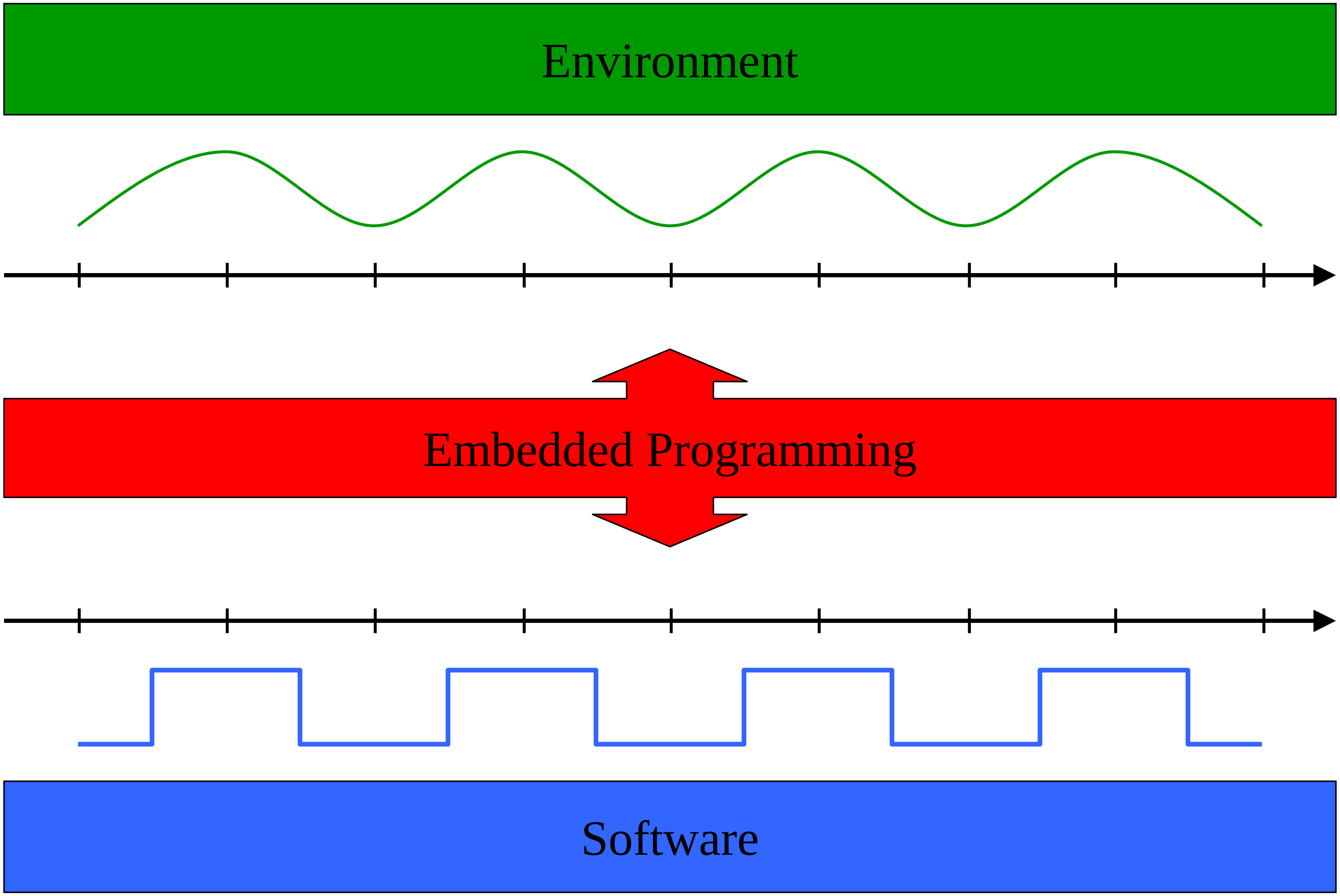
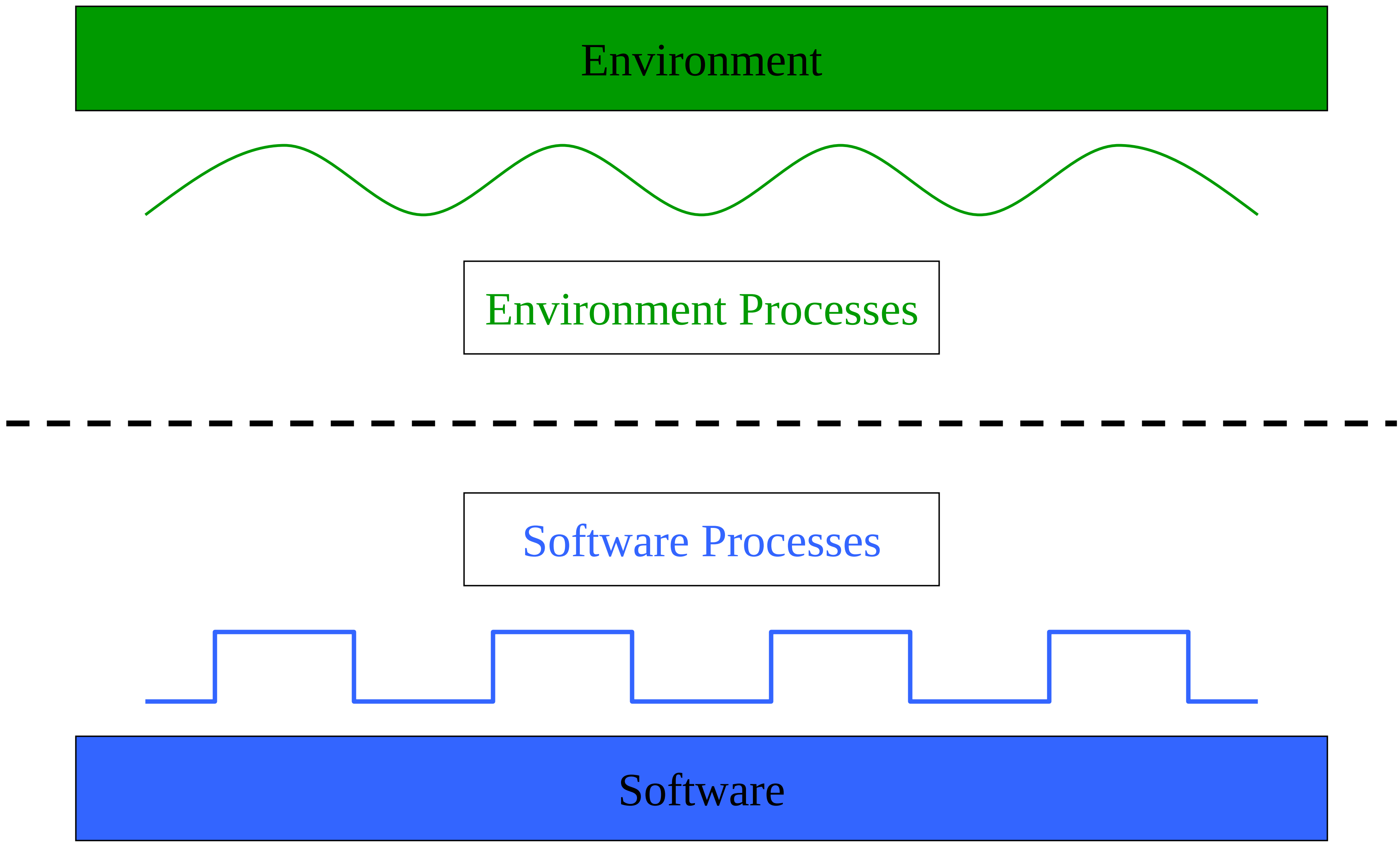
www.eecs.berkeley.edu/~fresco/giotto/course-2002

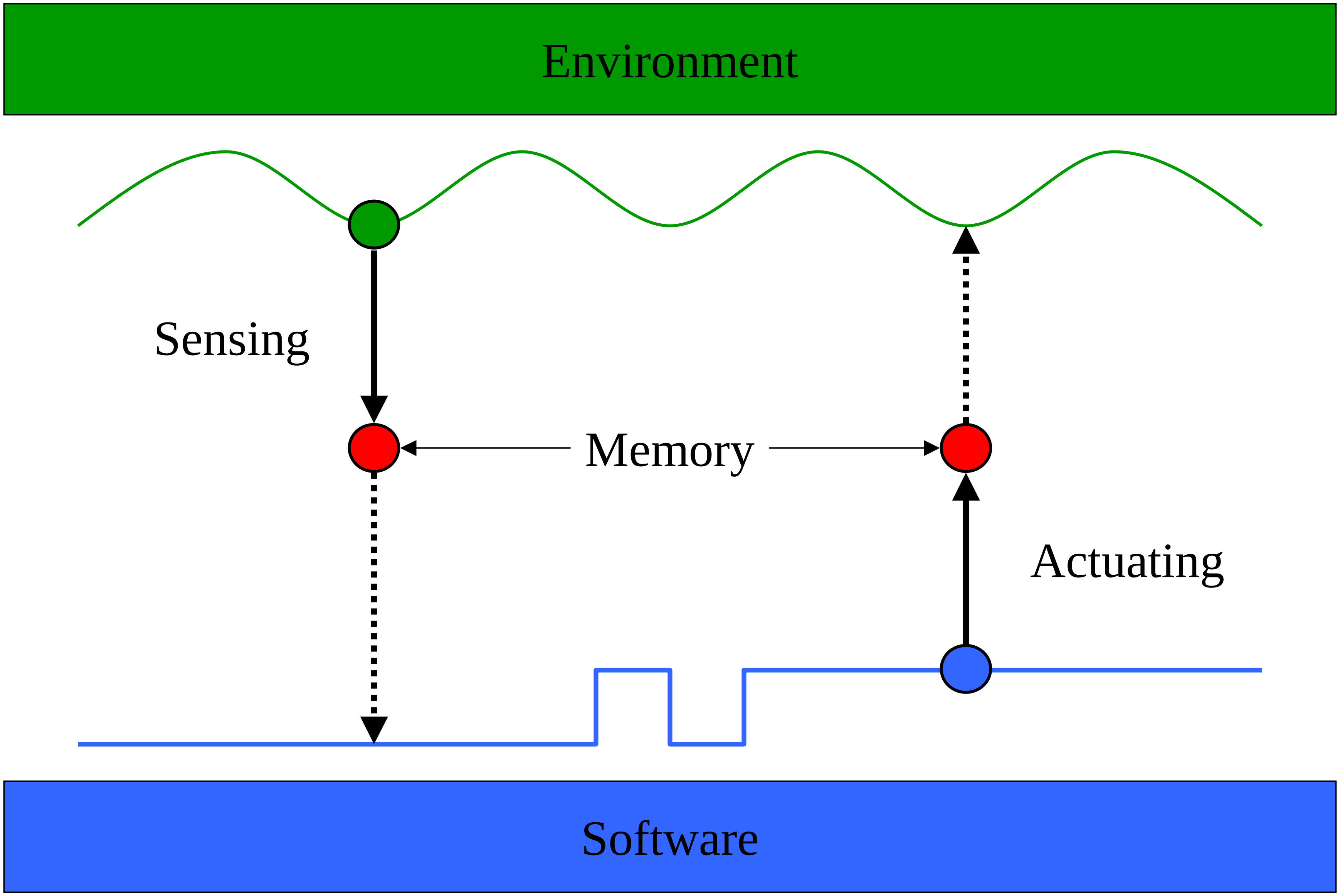
The Art of Embedded Programming



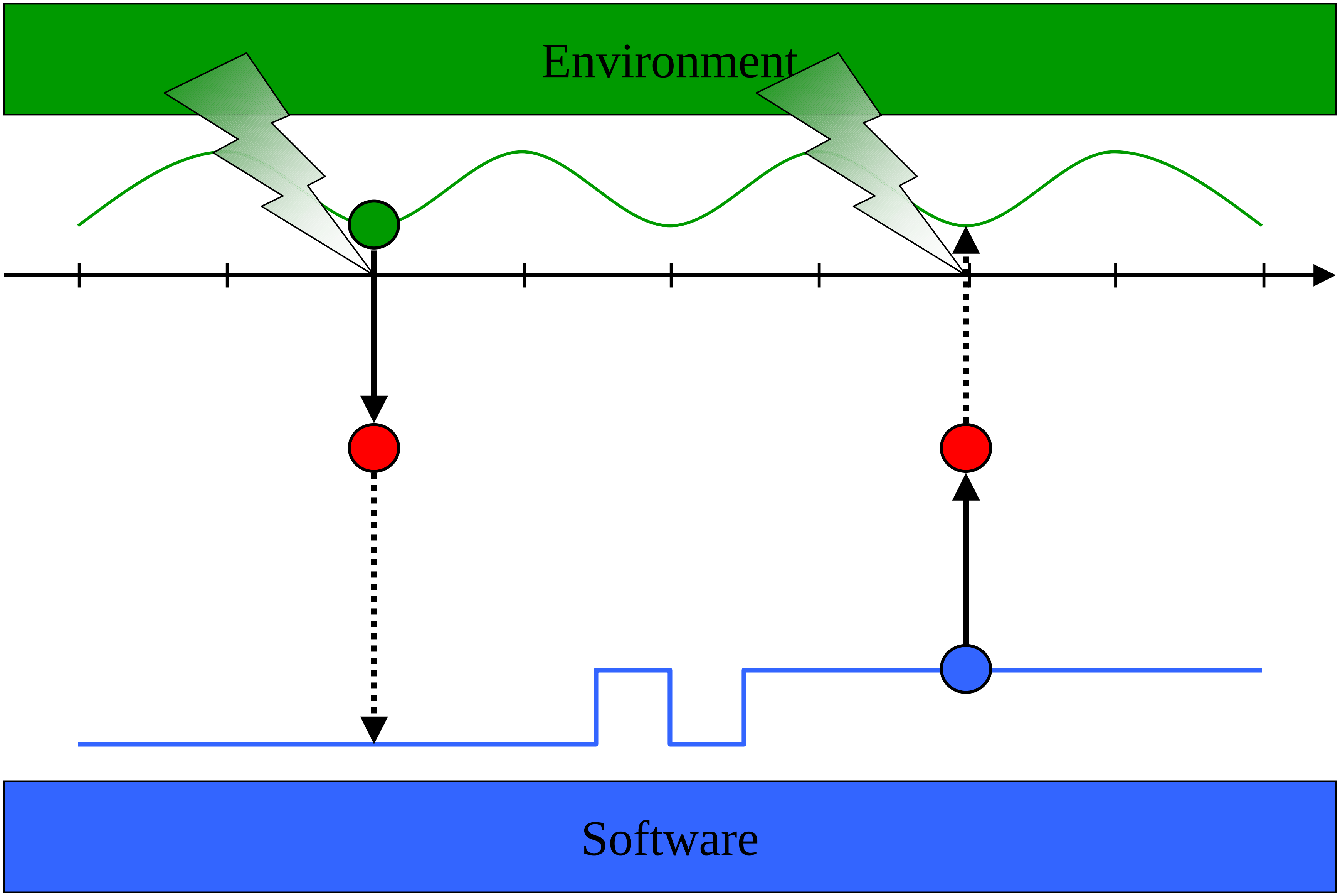
What Do We Really Need From an RTOS?



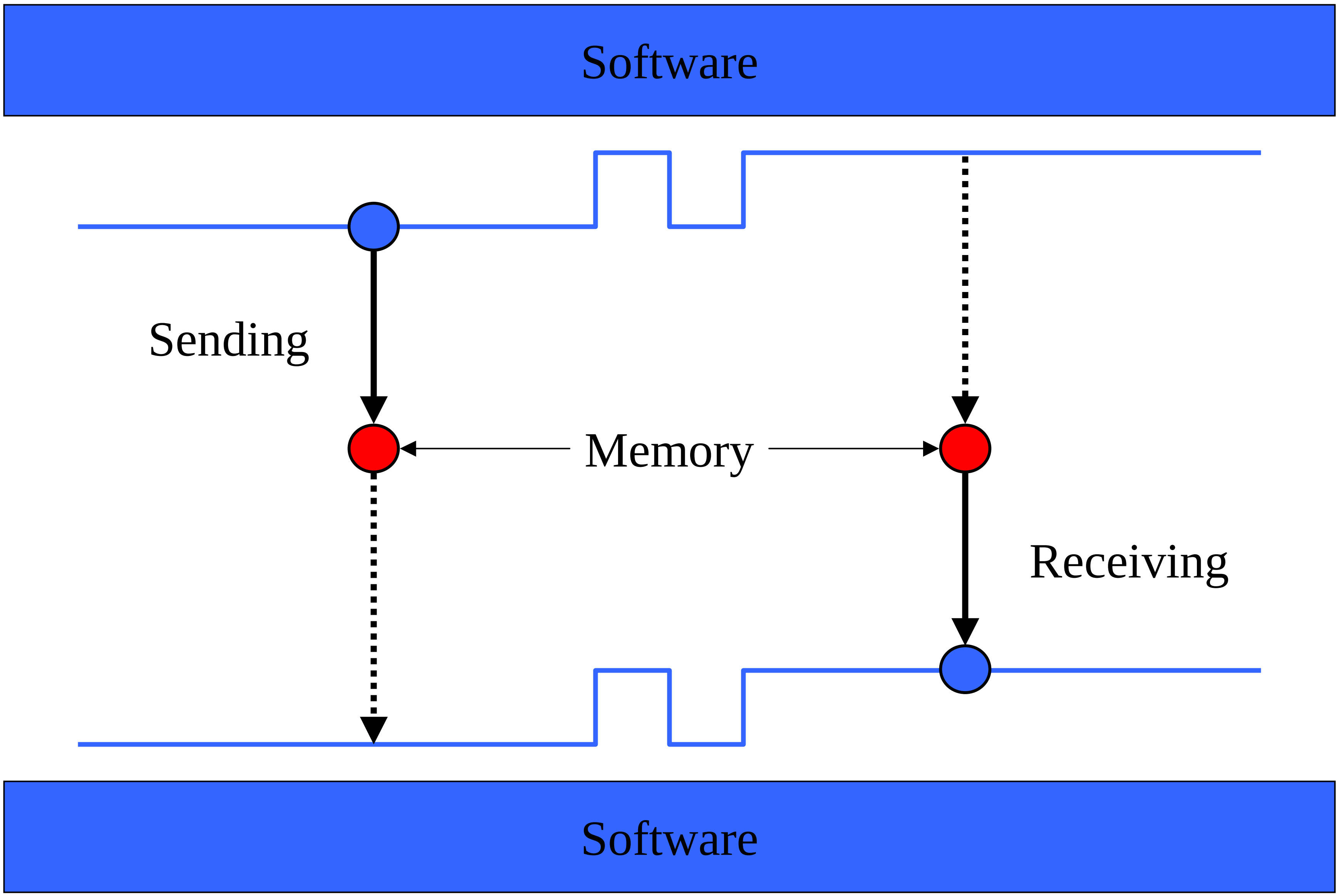
Environment Communication Services



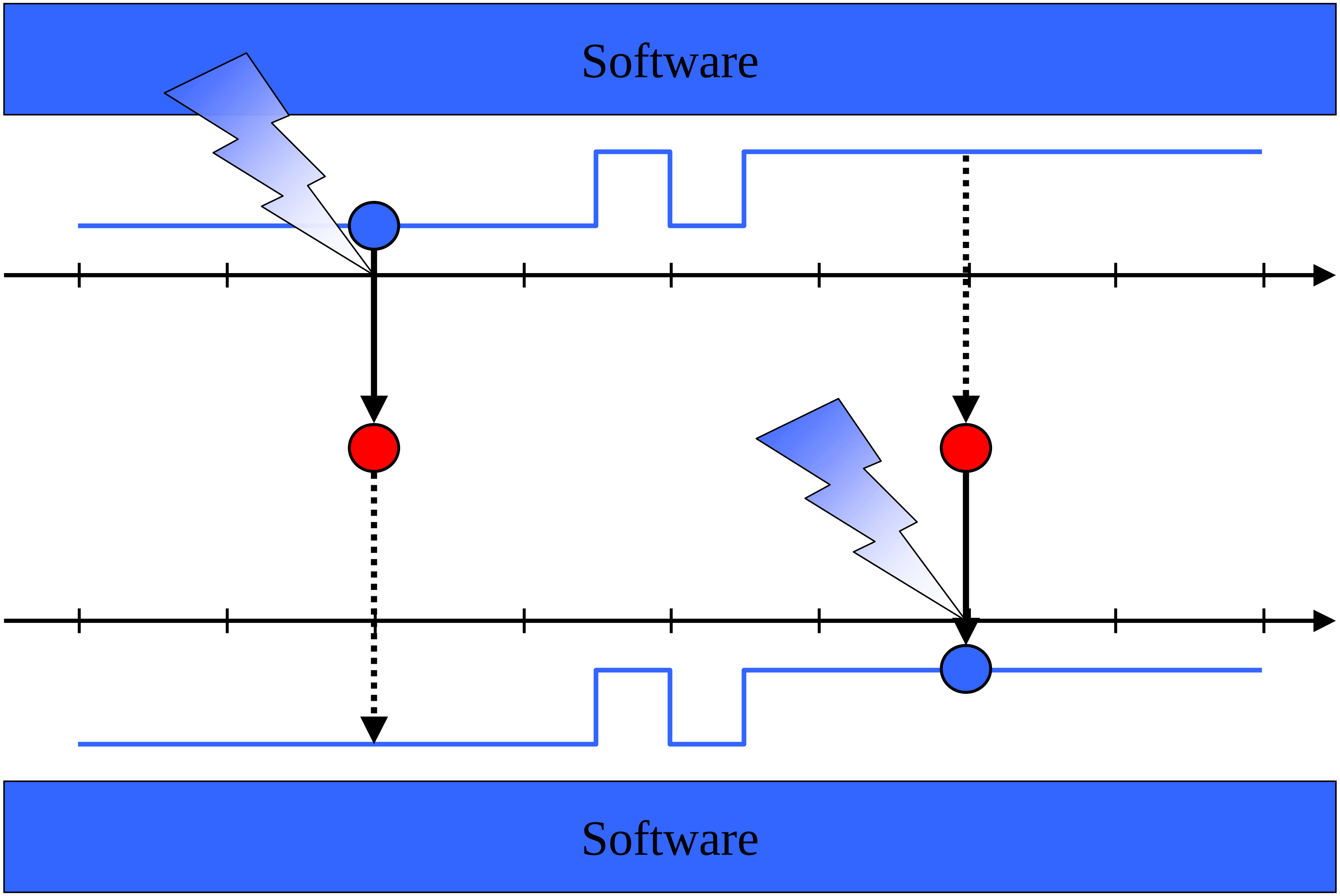
Environment Trigger Services



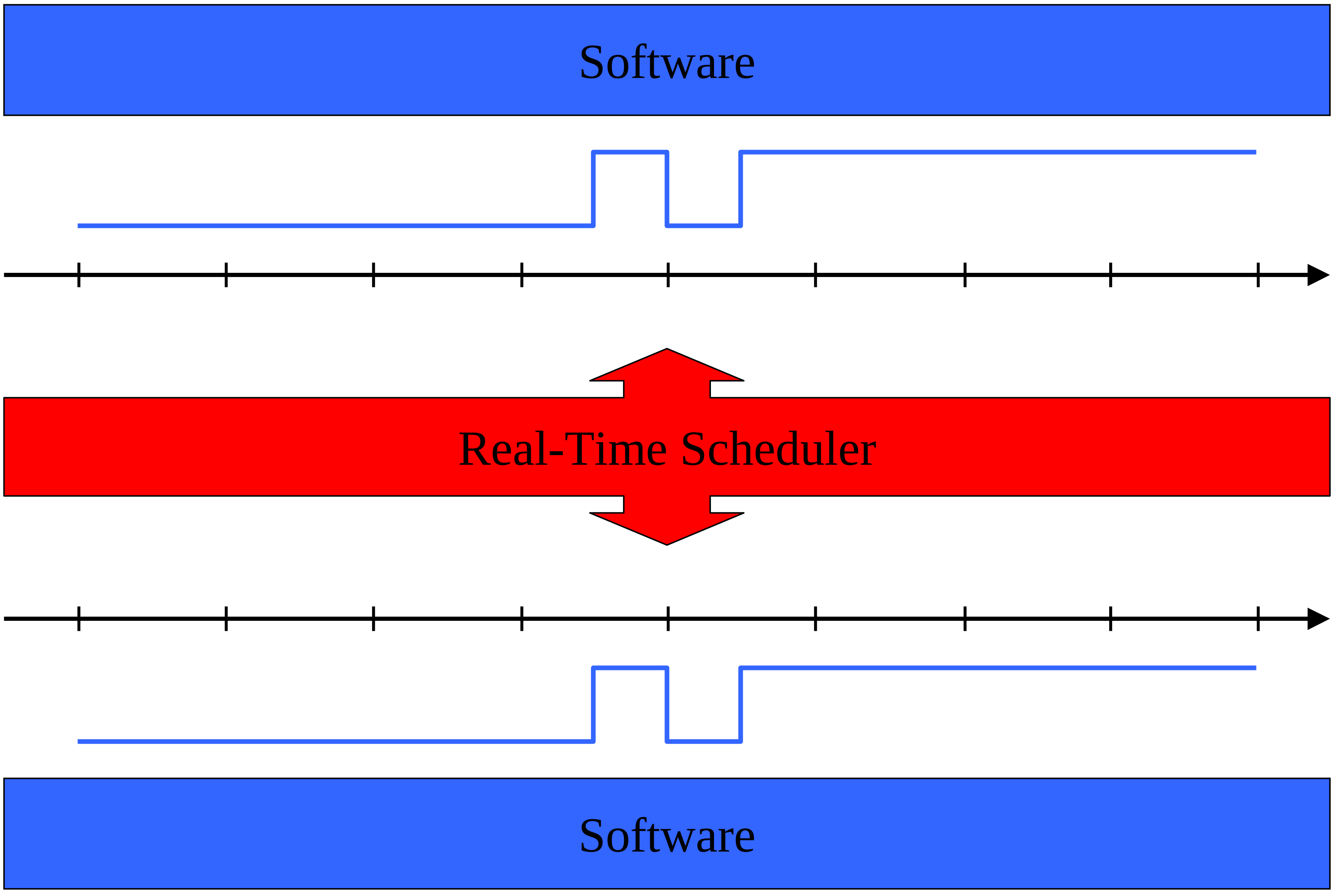
Software Communication Services



Software Trigger Services



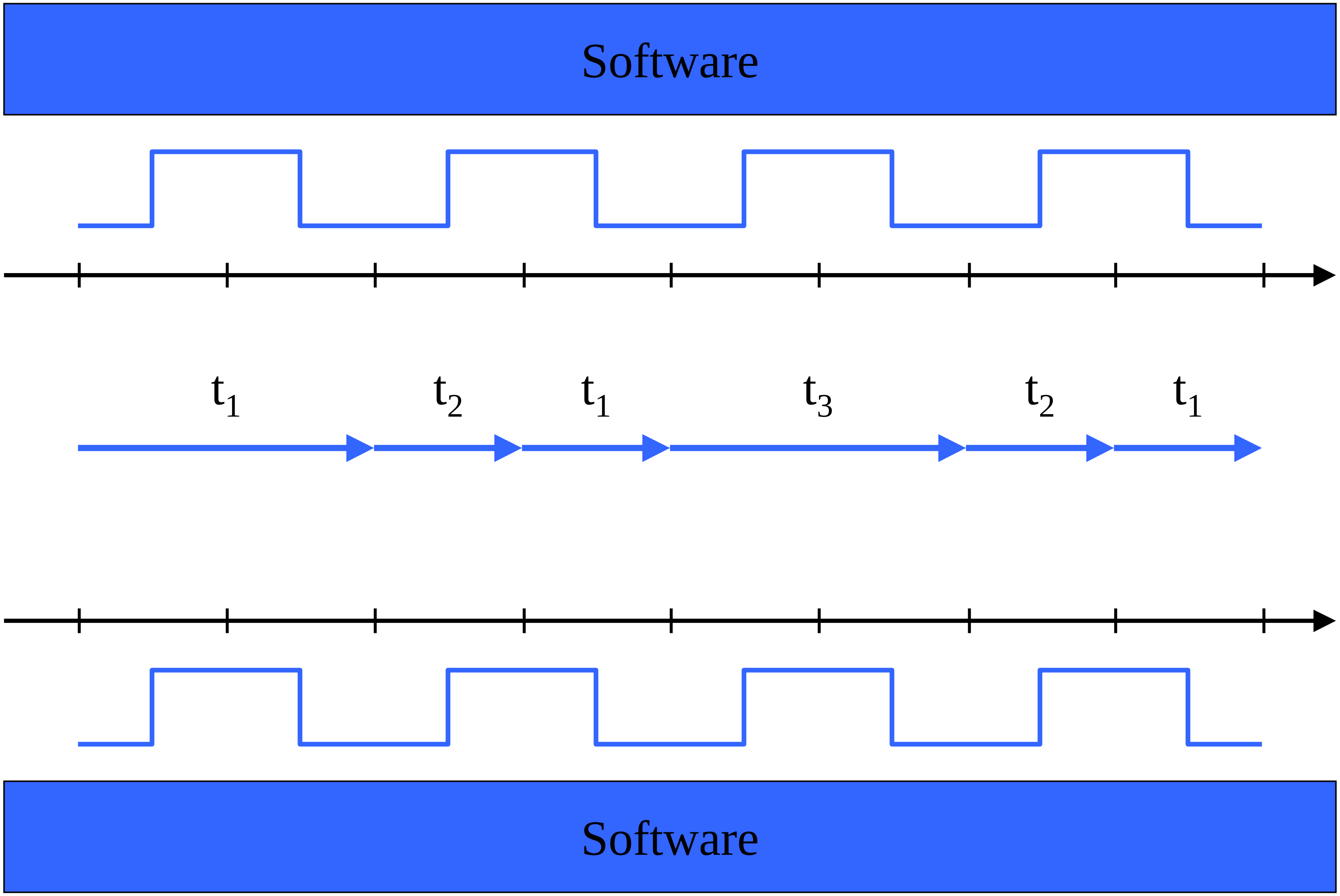
Software Scheduling Services



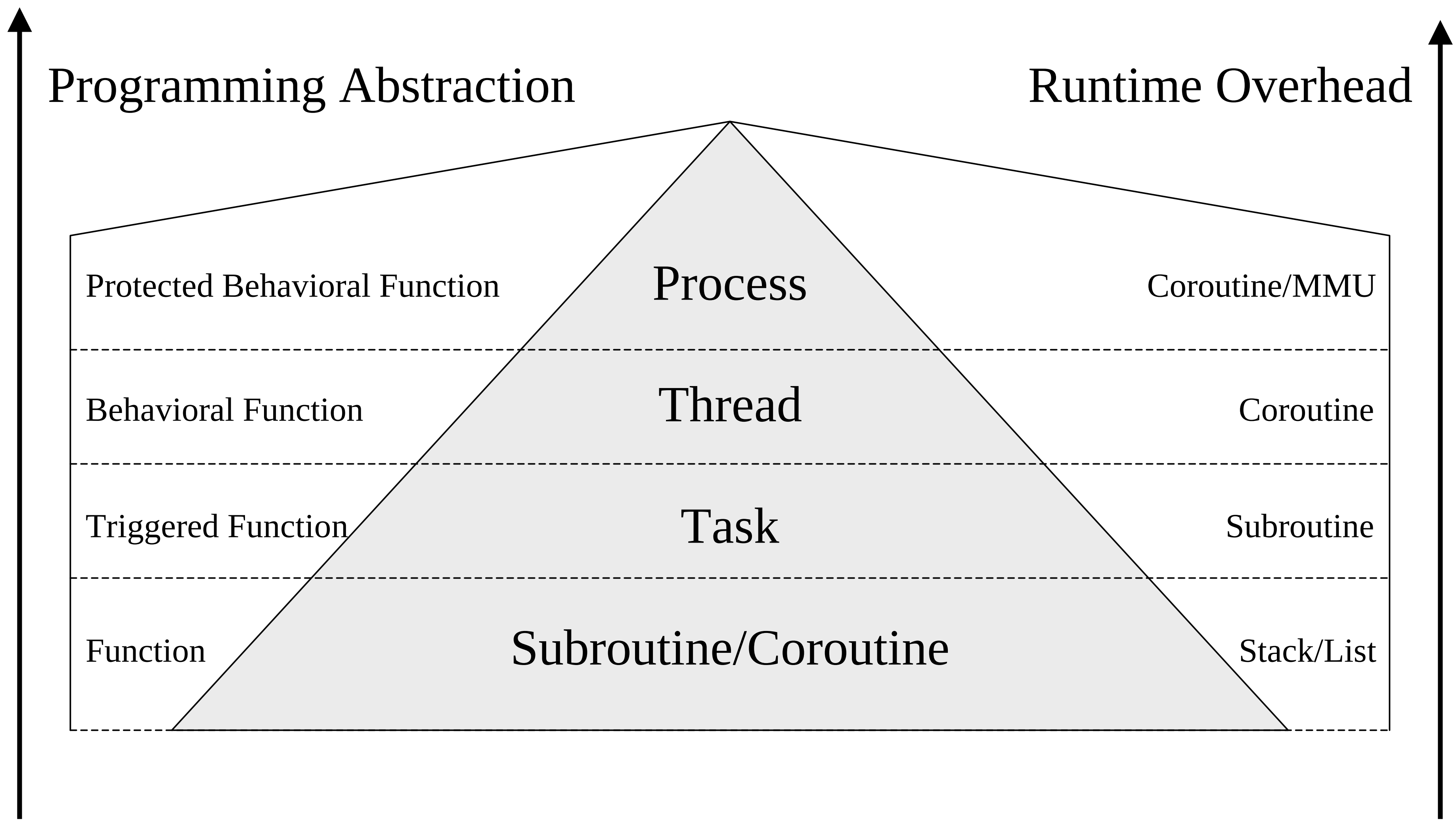
Summary: RTOS Services

Service	Implementation
Sensing/Actuating	Device Drivers
Environment Triggering	Interrupt Handlers
Software Communication	Shared Variables
Software Triggering	Signals
Software Scheduling	Scheduler

The Illusion of Concurrent Software



Abstractions for Multiprogramming



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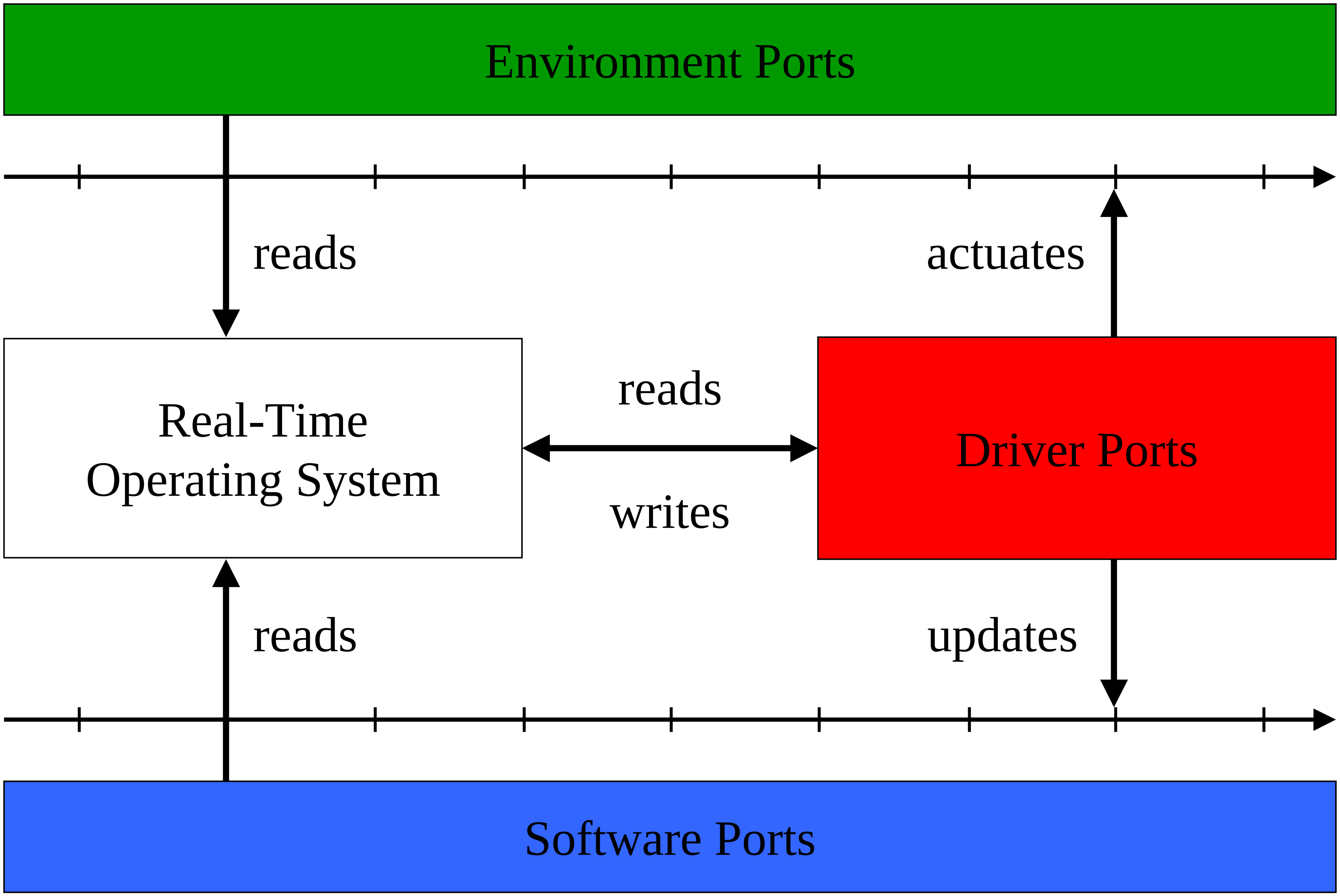
Memory Model



Definition: Task

- A task is a *function* from its input and state ports to its output and state ports

- A task *runs to completion* (cannot be killed)
- A task is *preemptable*

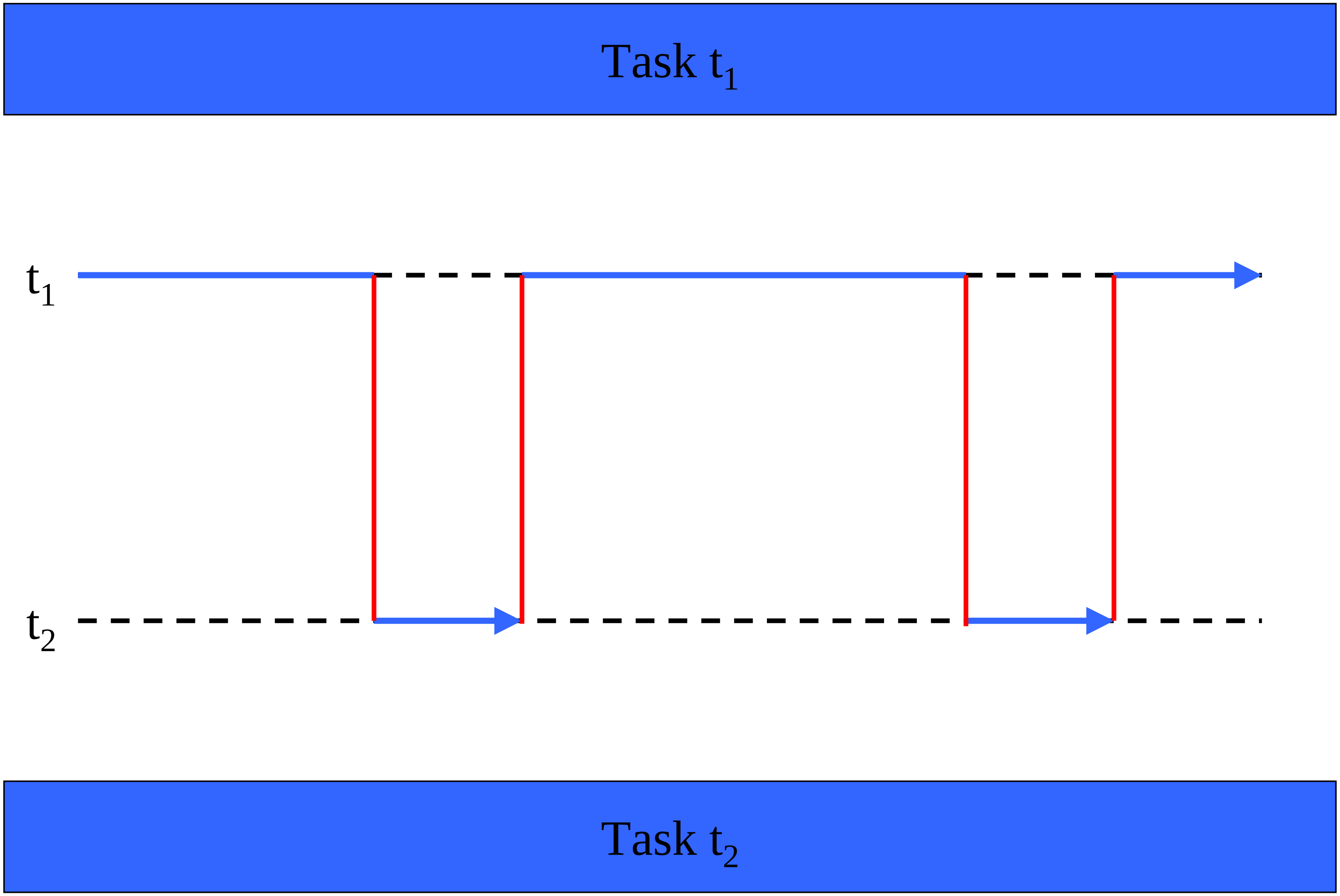
- A task does not use *signals* (except at completion)
- A task does not use *semaphores* (as a consequence)

- API (used by the RTOS):
  - `initialize` {task: state ports}
  - `schedule` {task}
  - `dispatch` {task: function}

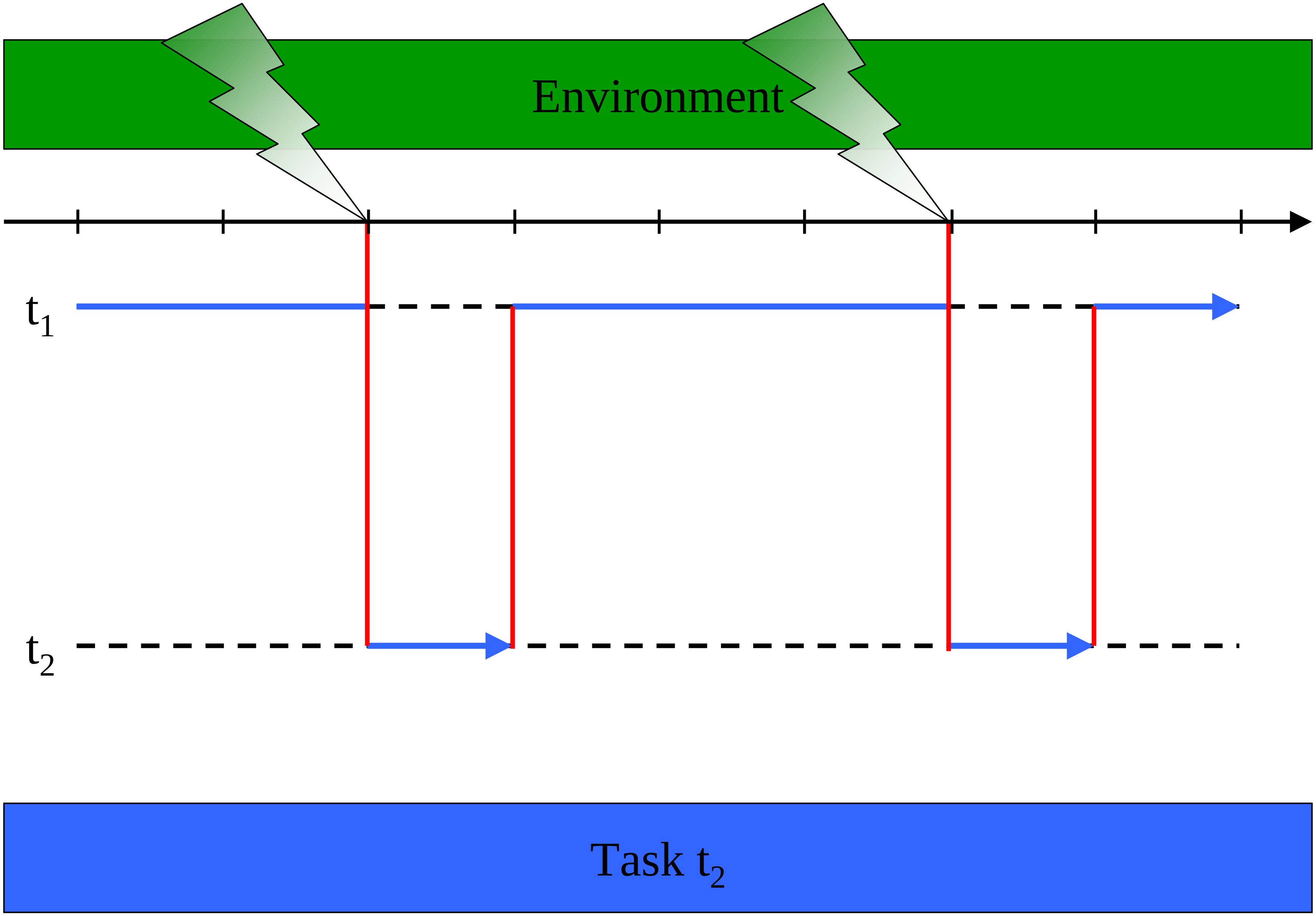
So, what's the difference between a task and a function?

- A task has an operational semantics:
  - A task is implemented by a *subroutine* and a *trigger*
  - A task is either *environment*- or *software-triggered*
  - The completion of a task may trigger another task

Task t_2 Preempts Task t_1



Who Triggers Task t_2?



Definition: Event and Signal

- An event is a *change of state* in some environment ports
- A signal is a *change of state* in some software ports

- A synchronous signal is a *change of state* in some driver ports

Definition: Trigger

- A trigger is a *predicate* on environment, software, driver ports

- A trigger *awaits* events and/or signals
- A trigger is *enabled* if its predicate evaluates to true
- Trigger evaluation is *atomic* (non-preemptable)

- A trigger can be *activated* by the RTOS
- A trigger can be *cancelled* by the RTOS
- A trigger can be *enabled* by an event or a signal

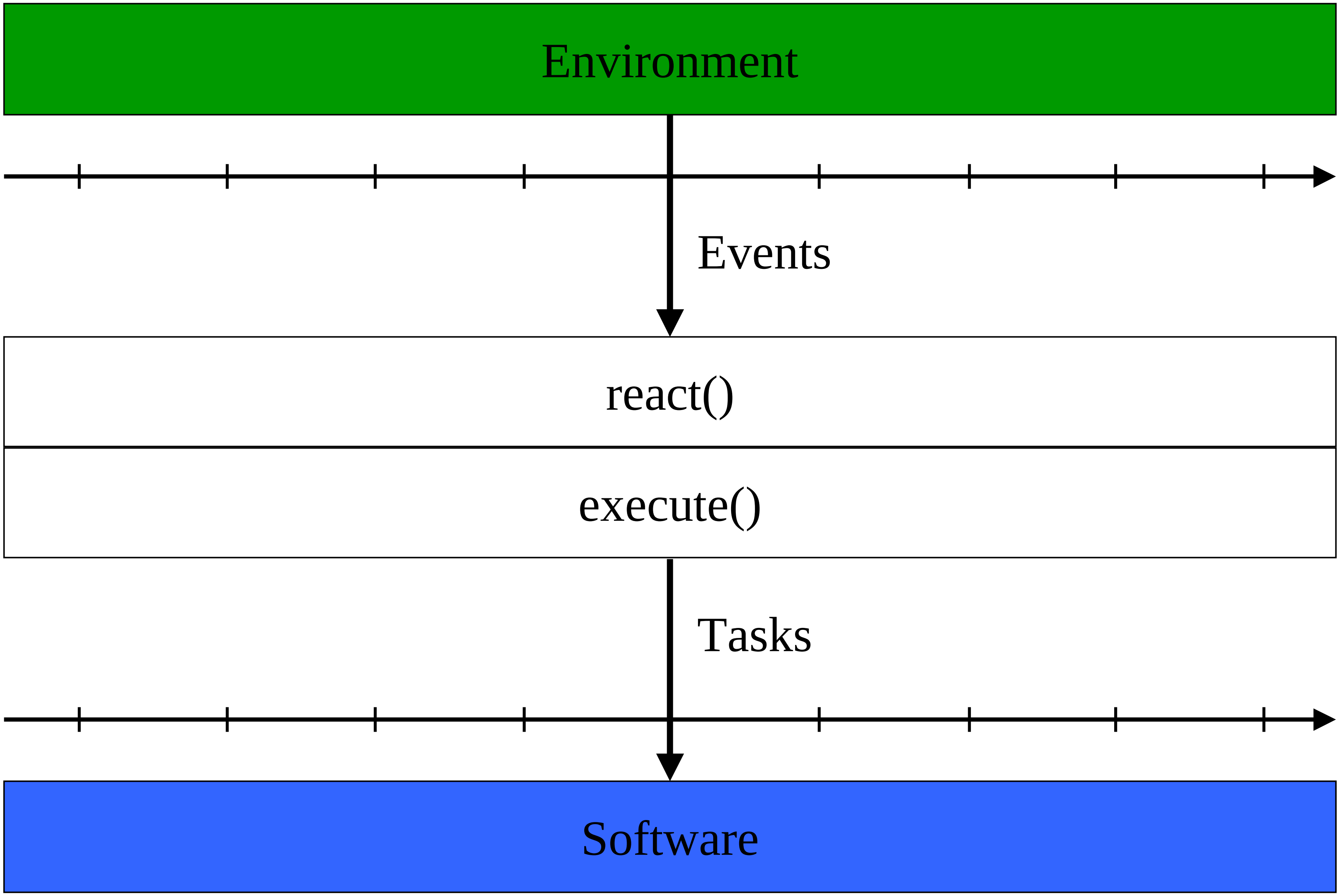
- API (used by the RTOS):
  - `activate` {trigger}
  - `cancel` {trigger}
  - `evaluate` {trigger: predicate}

My First RTOS

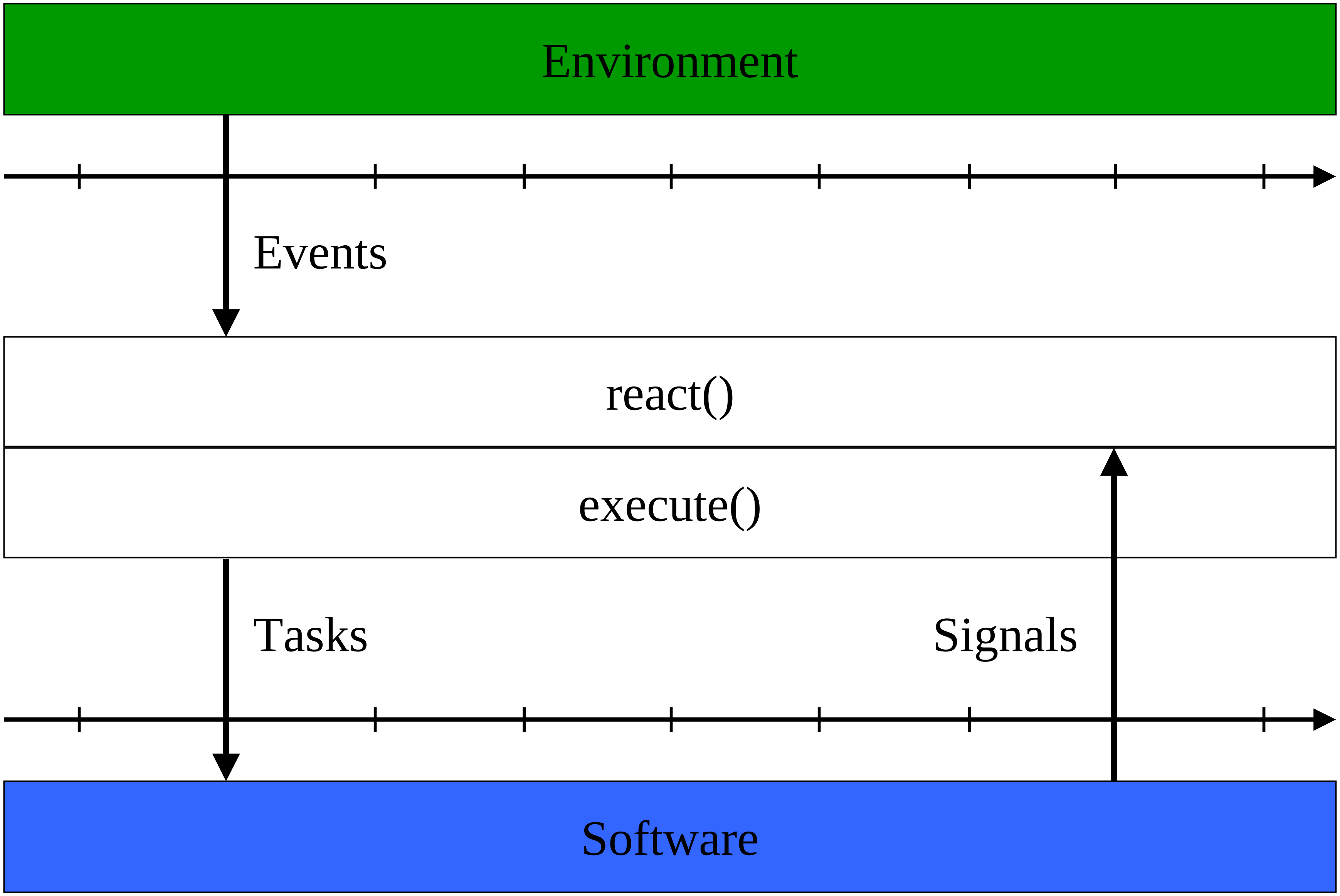
```
∀ tasks  t:  initialize(t);
∀ triggers g:  activate(g);
while (true) {
  if ∃ active-trigger g:  evaluate(g) == true then
    execute();
}
```

```
execute() {
  scheduled-tasks := ∀ triggered-tasks t:  schedule(t);
  ∀ scheduled-tasks t:  dispatch(t);
}
```

RTOS Model: Reaction vs. Execution



RTOS Model with Signals



RTOS with Preemption

```
∀ tasks t: initialize(t);
∀ triggers g: activate(g);
while (true) {
  if ∃ active-trigger g: evaluate(g) == true then
    execute_concurrently();
}
```

```
execute_concurrently() {
  scheduled-tasks := ∀ triggered-tasks t: schedule(t);
  ∀ scheduled-tasks t: dispatch(t);
}
```

Corrected RTOS with Preemption

```
∀ tasks t: initialize(t);
∀ triggers g: activate(g);
while (true) {
  if ∃ active-trigger g: evaluate(g) == true then
    execute_concurrently();
}
```

```
execute_concurrently() {
  ∀ triggers g: cancel(g);
  scheduled-tasks := ∀ triggered-tasks t: schedule(t);
  ∀ triggers g: activate(g);

  ∀ scheduled-tasks t: dispatch(t);
}
```

Definition: Thread

- A thread is a *behavioral function* (with a trace semantics)

- A thread *may be killed*
- A thread is *preemptable*

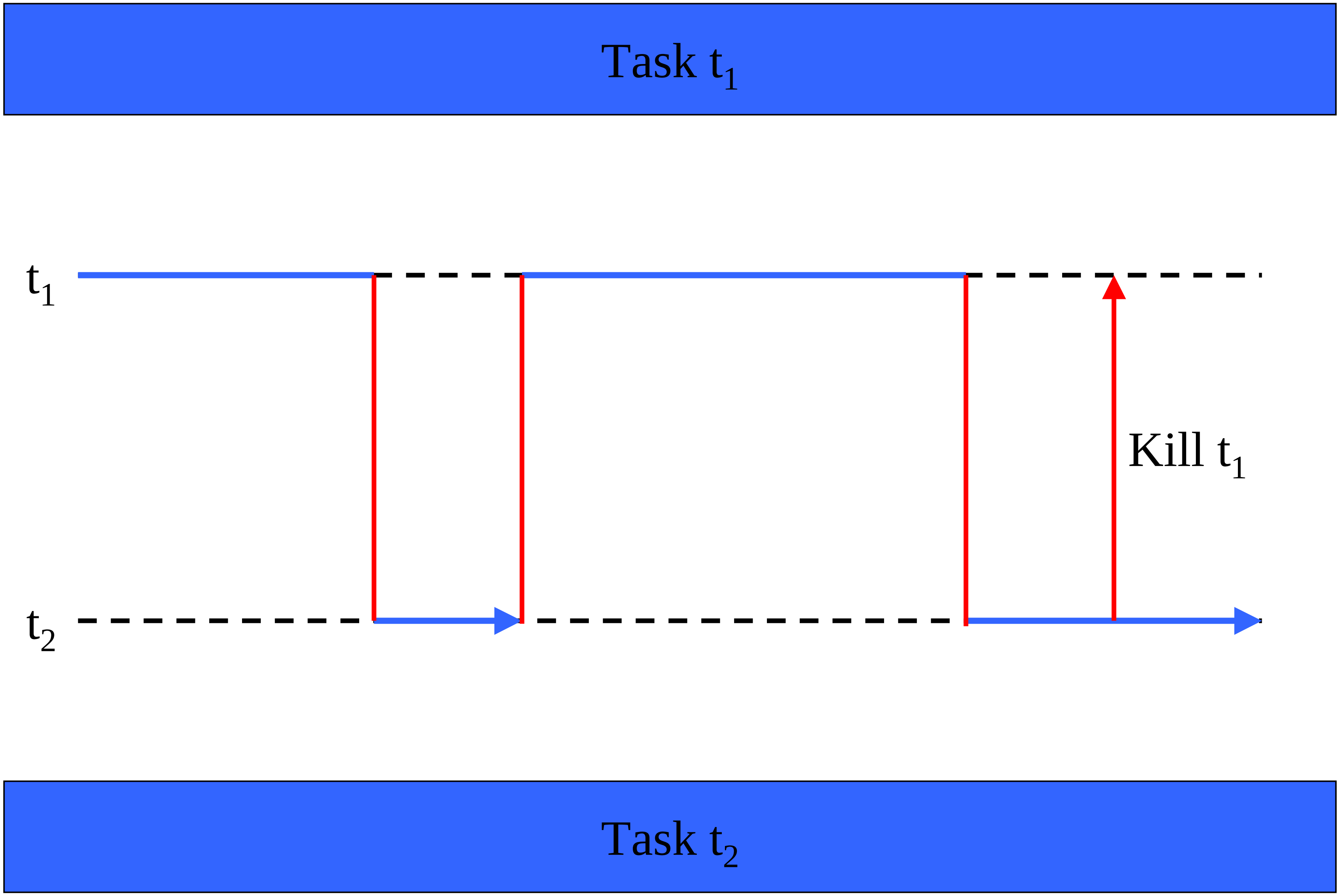
- A thread may use *signals*
- A thread may use *semaphores*

- API (used by the RTOS or threads):
  - `initialize` {thread: ports}
  - `schedule` {thread}
  - `dispatch` {thread: function}
  - `kill` {thread}

So, what’s the difference between a thread and a task?

- A thread is a *collection* of tasks:
    - A thread is implemented by a *coroutine*
    - A thread requires signals

Task t_2 Kills Task t_1: Coroutine



Signal API

- A signal can be *awaited* by a thread
- A signal can be *emitted* by a thread
- Signal emission is *atomic* (non-preemptable)

- API (used by threads):
  - `wait` {signal}
  - `emit` {signal}

- Literature:
  - emit: send(signal)

Definition: Semaphore

- A semaphore consists of a *signal* and a *port*

- A semaphore can be *locked* by a thread
- A semaphore can be *released* by a thread
- Semaphore access is *atomic* (non-preemptable)

- API (used by threads):
  - `lock` {semaphore}
  - `release` {semaphore}

- Literature:
  - lock: P(semaphore)
  - release: V(semaphore)

Binary Semaphore (Signal)

```
lock(semaphore) {
  if (semaphore.lock == true) then
    wait(semaphore.signal);

  semaphore.lock := true;
}

release(semaphore) {
  semaphore.lock := false;
  emit(semaphore.signal);
}
```

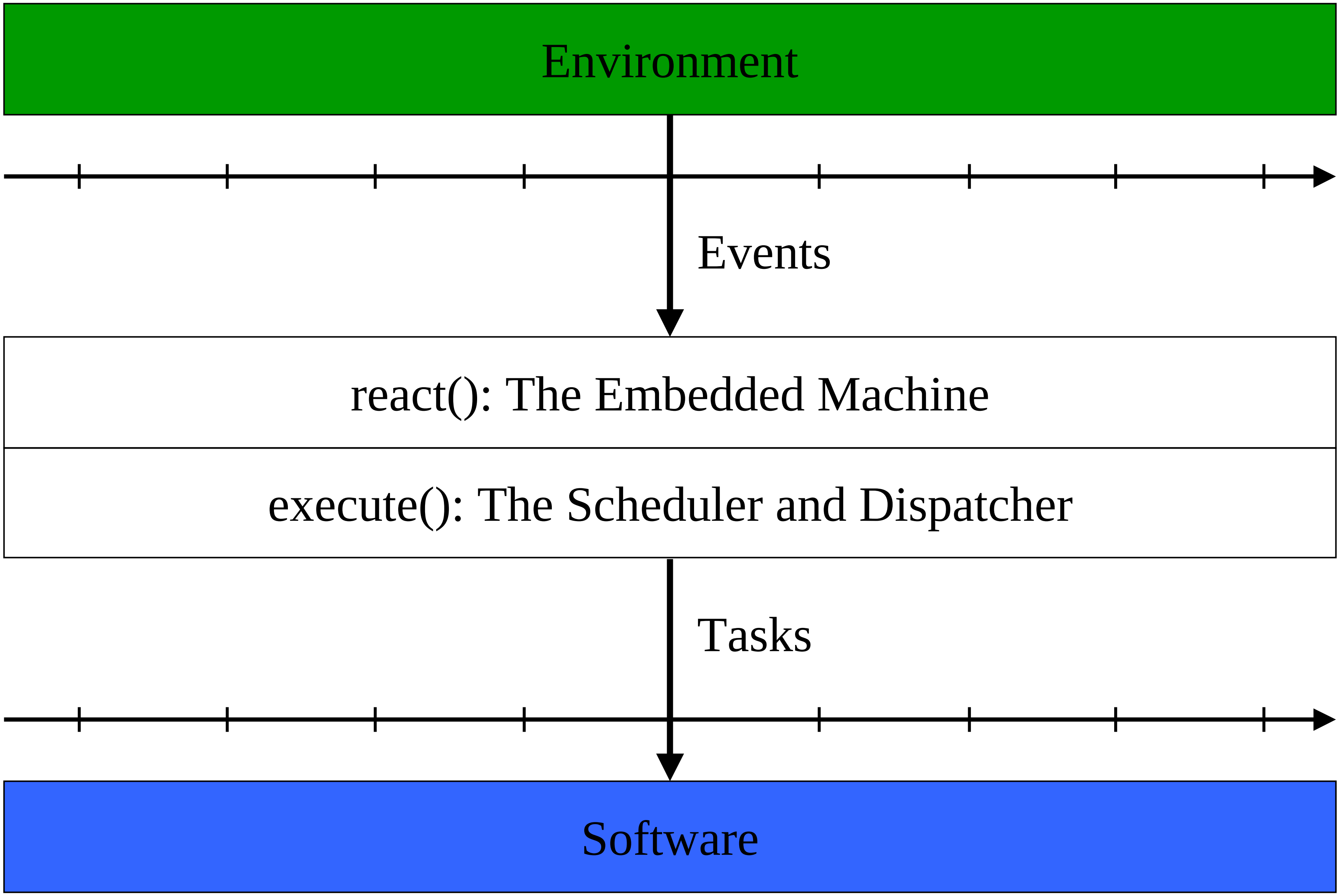
must be atomic

Binary Semaphore (Busy Wait)

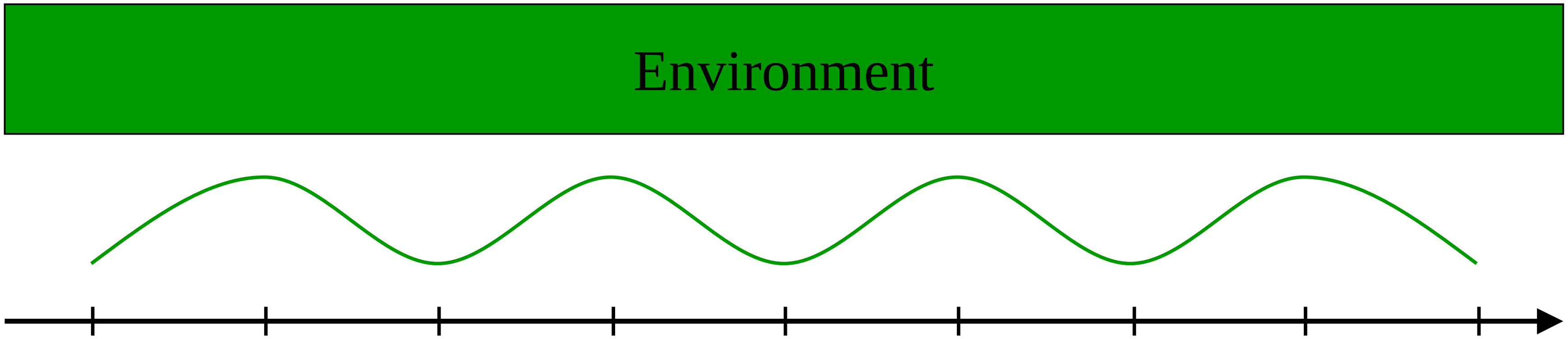
```
lock(semaphore) {
  while (semaphore.lock == true) do {}
  semaphore.lock := true;
}

release(semaphore) {
  semaphore.lock := false;
}
```

each round must be atomic

The Embedded Machine

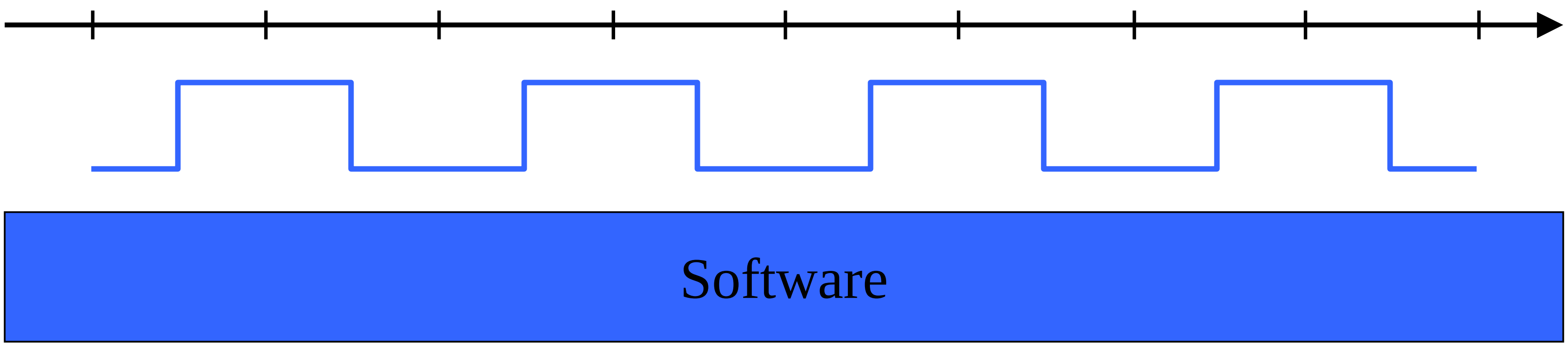


Proposal

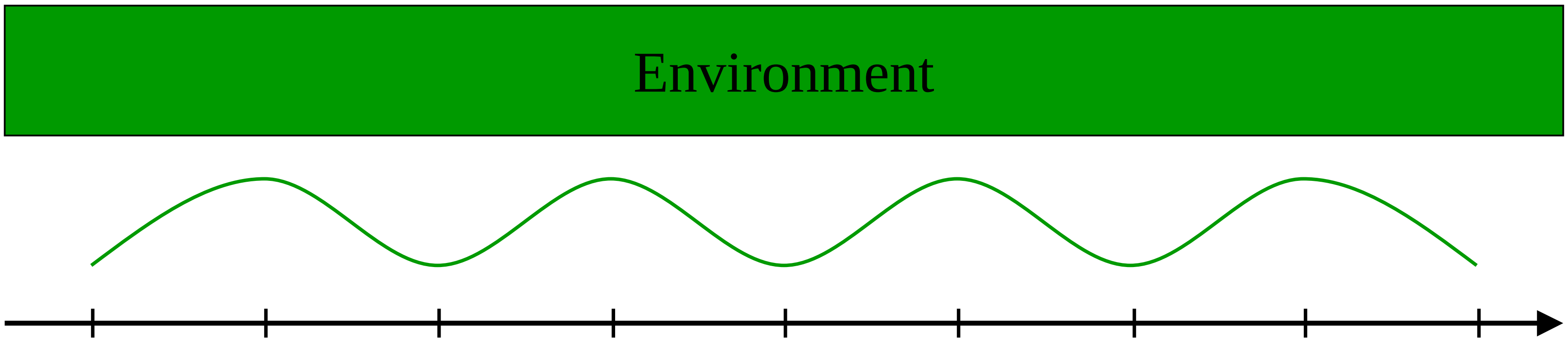


Human: Programming in terms of environment time

Compiler: Implementation in terms of platform time

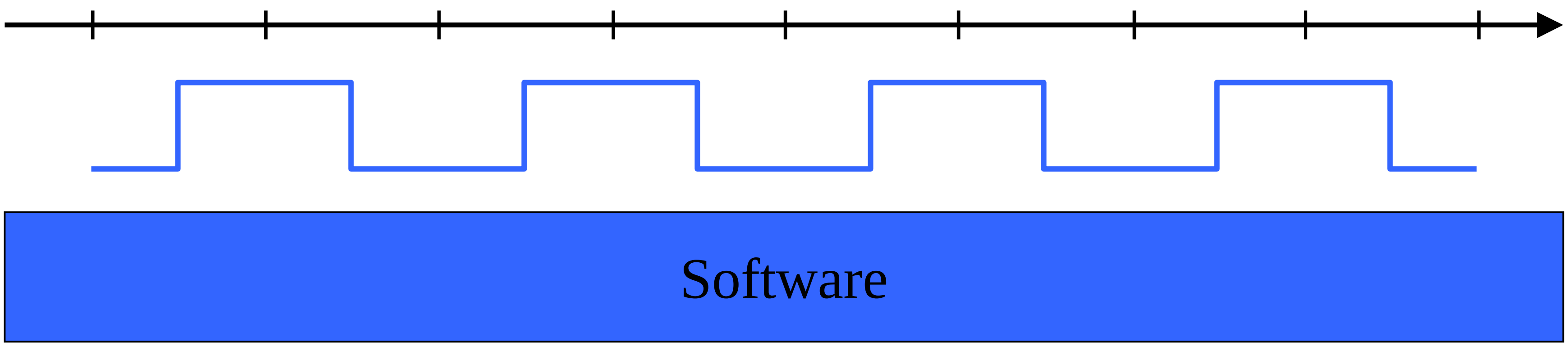


Platform Time is Platform Memory

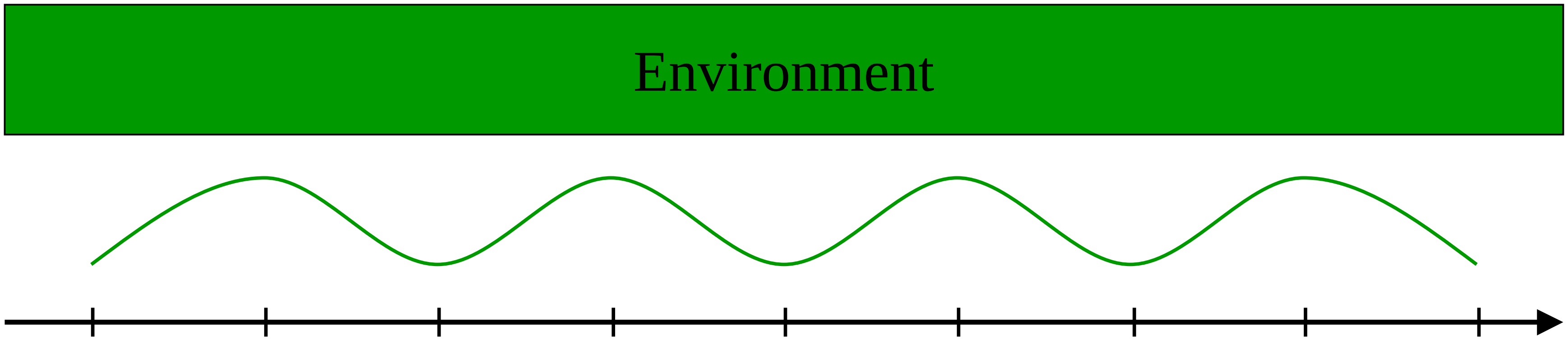


- Programming as if there is enough platform time

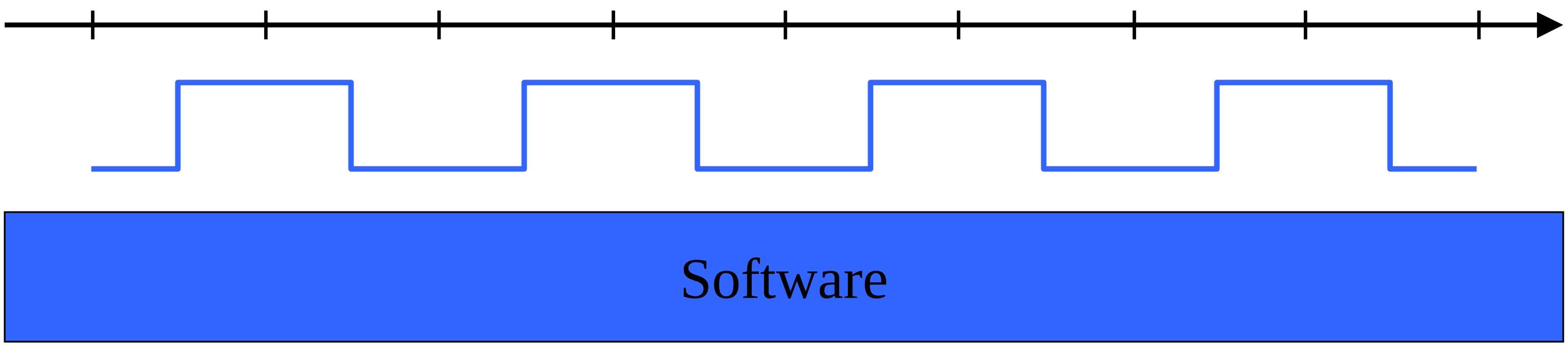
- Implementation checks whether there is enough of it



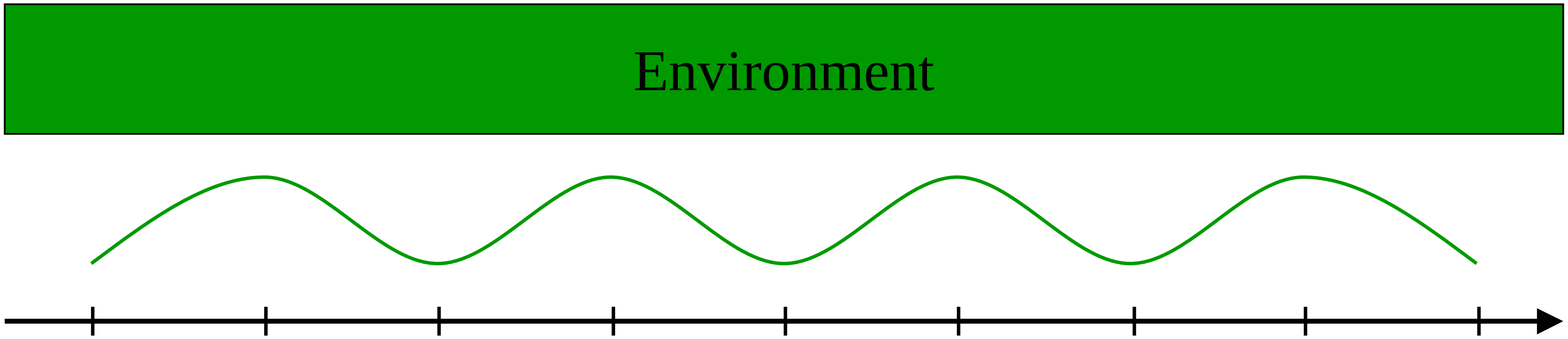
Portability



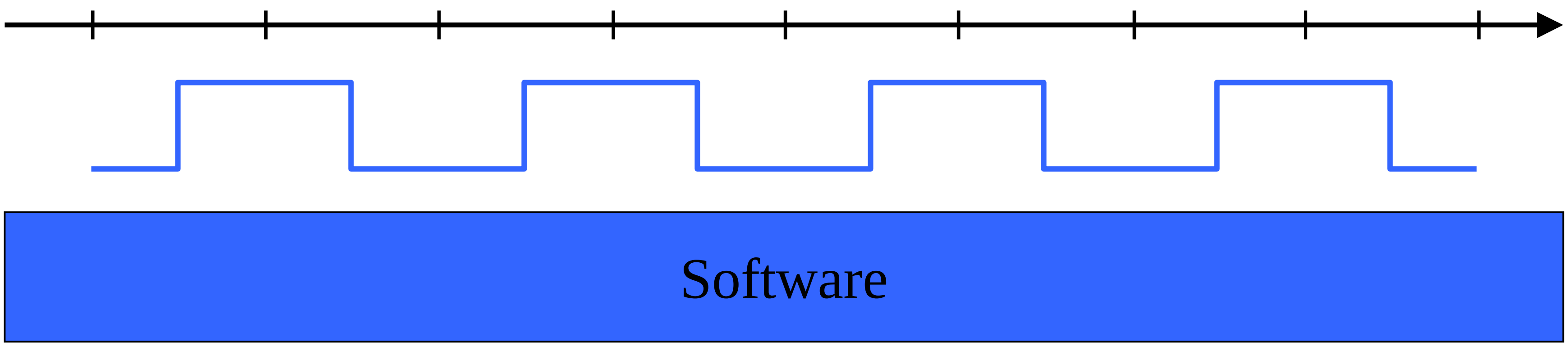
- Programming in terms of environment time yields platform-independent code



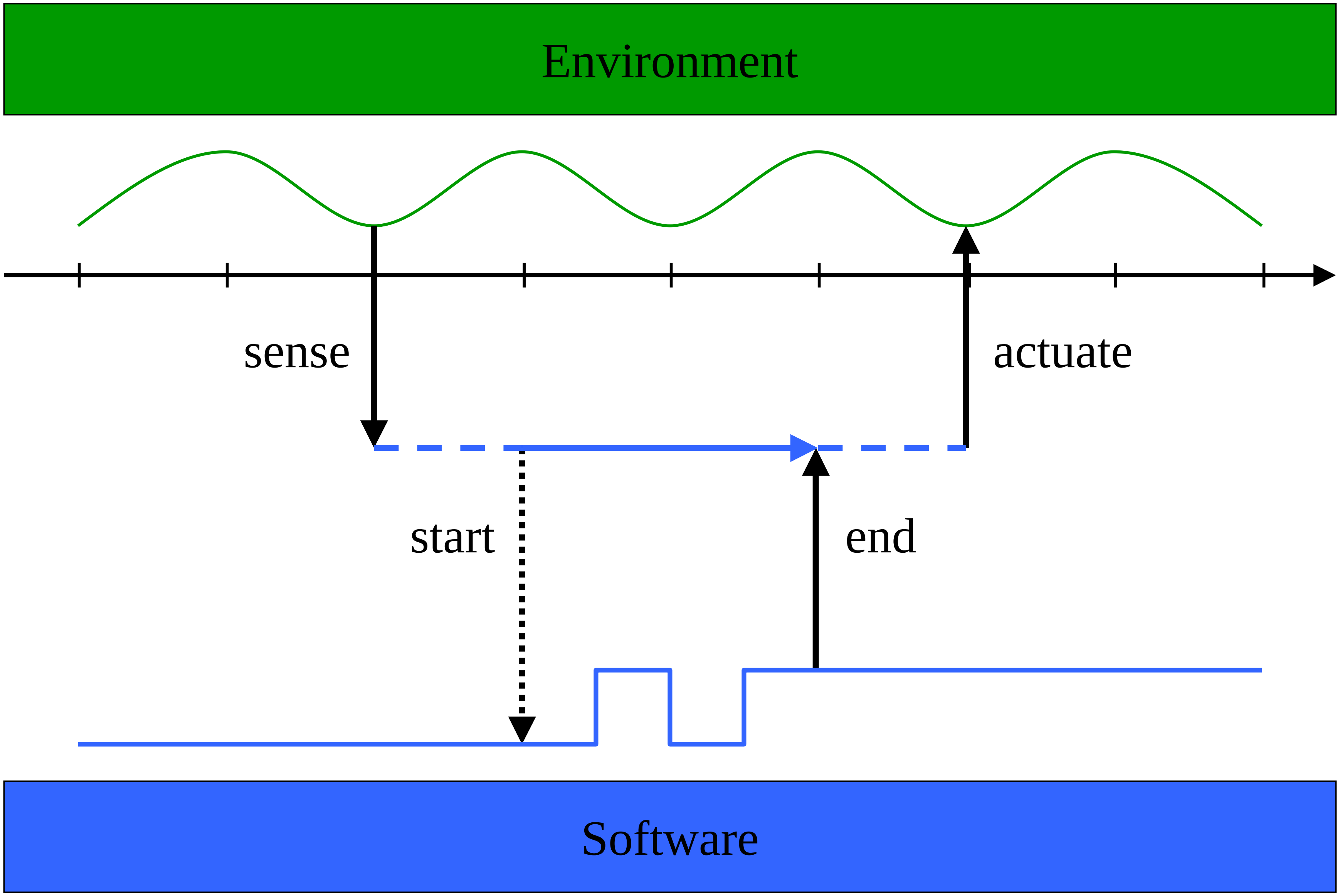
Predictability



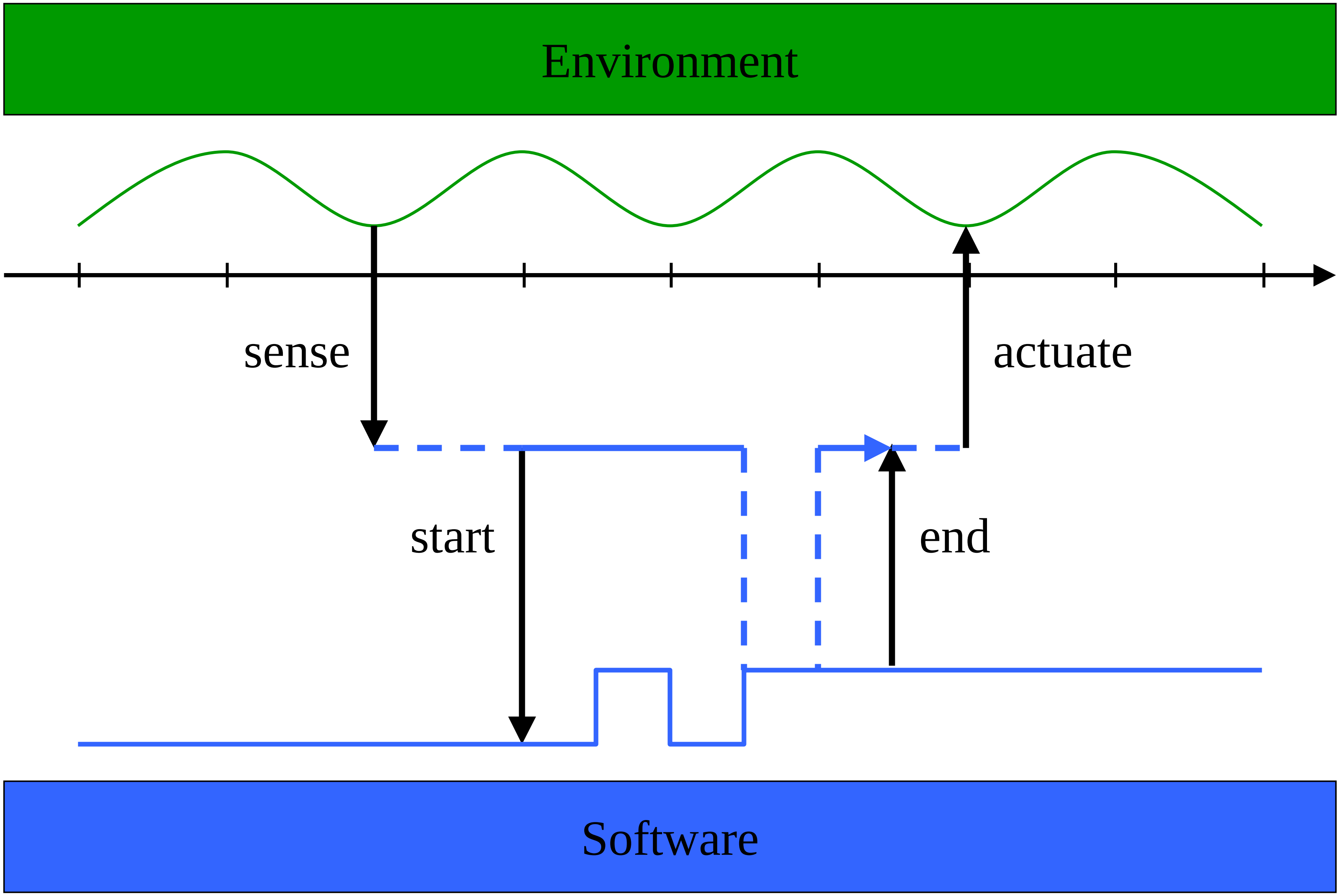
- Programming in terms of environment time yields <u>deterministic</u> code



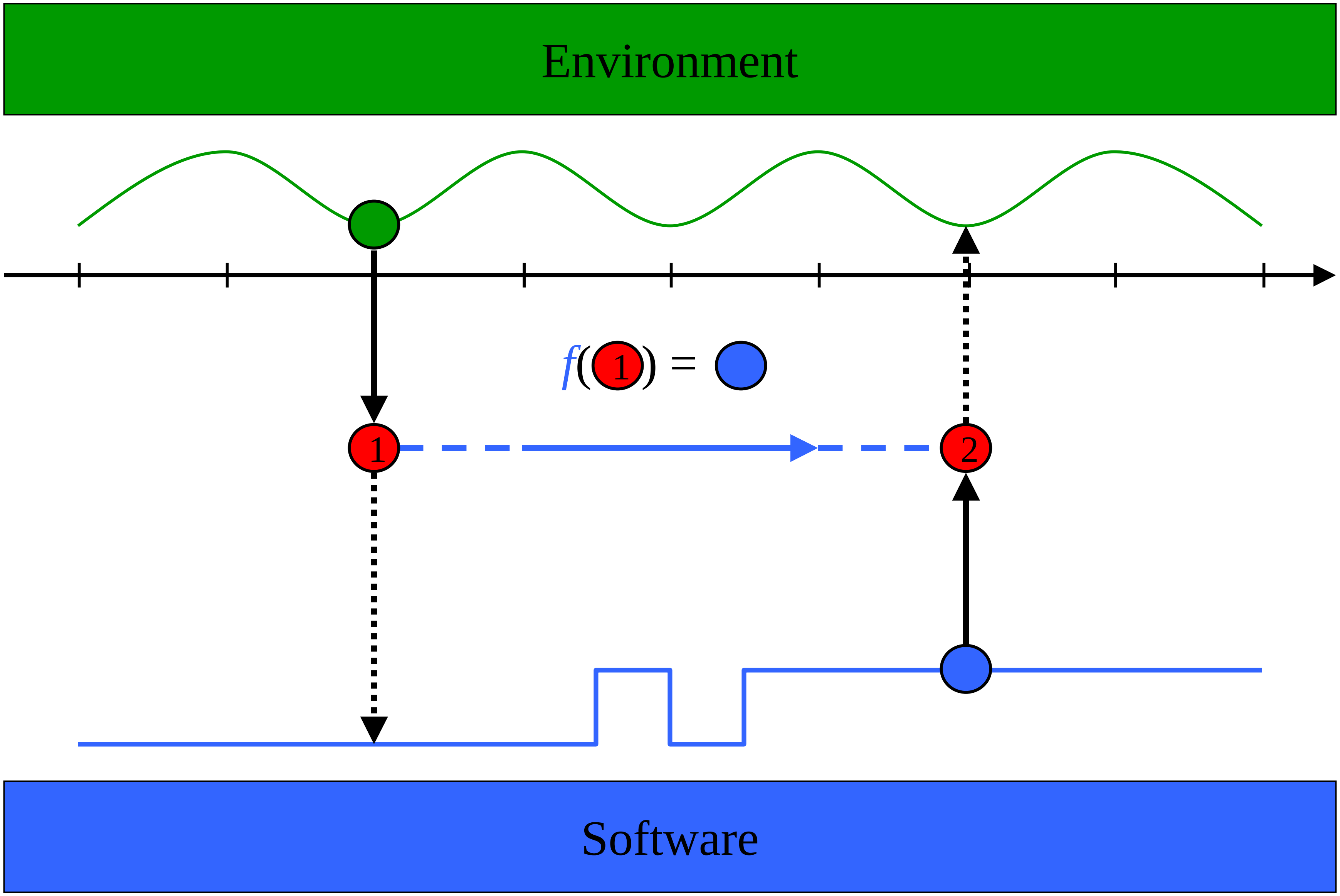
The Task Model



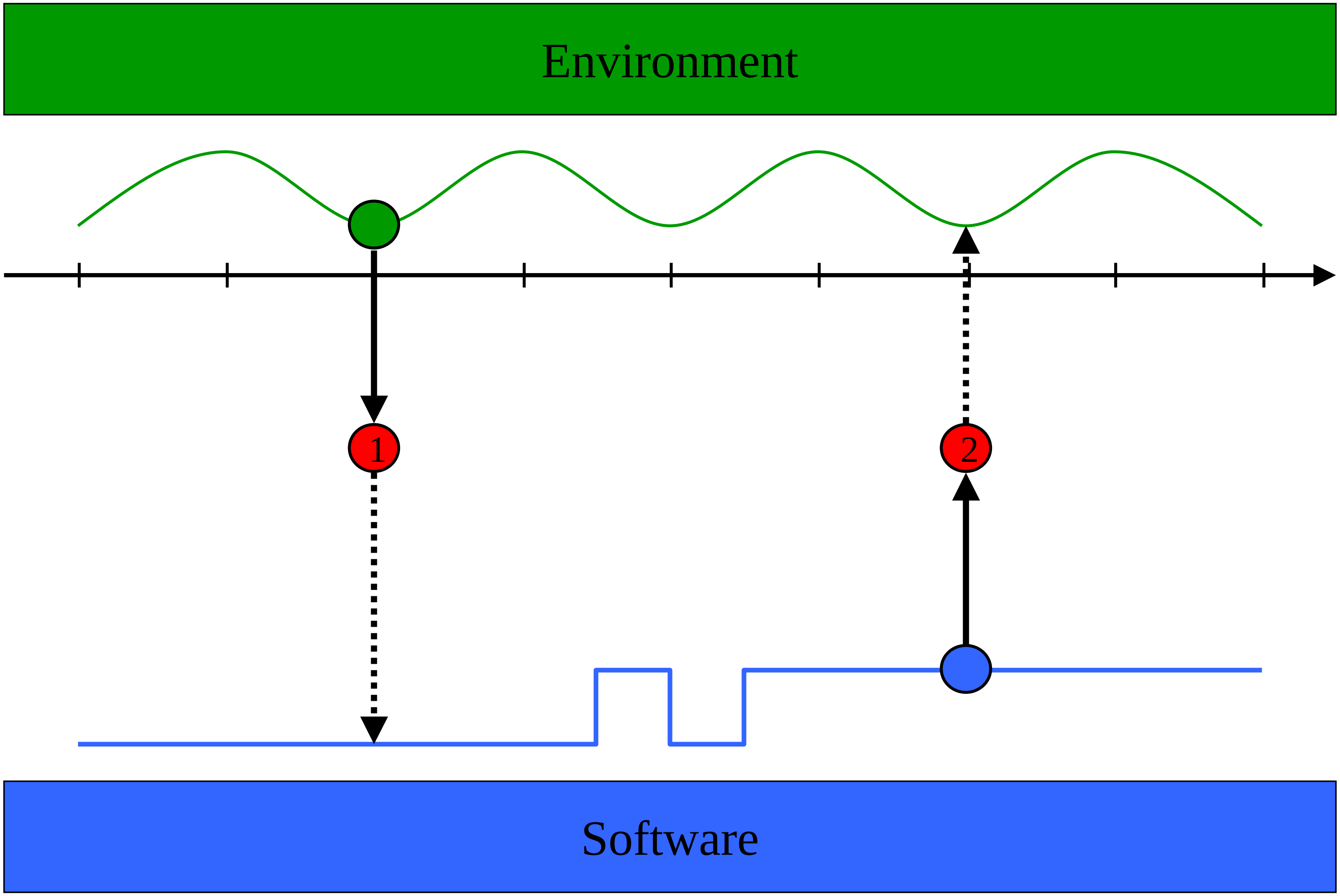
Preemptable…



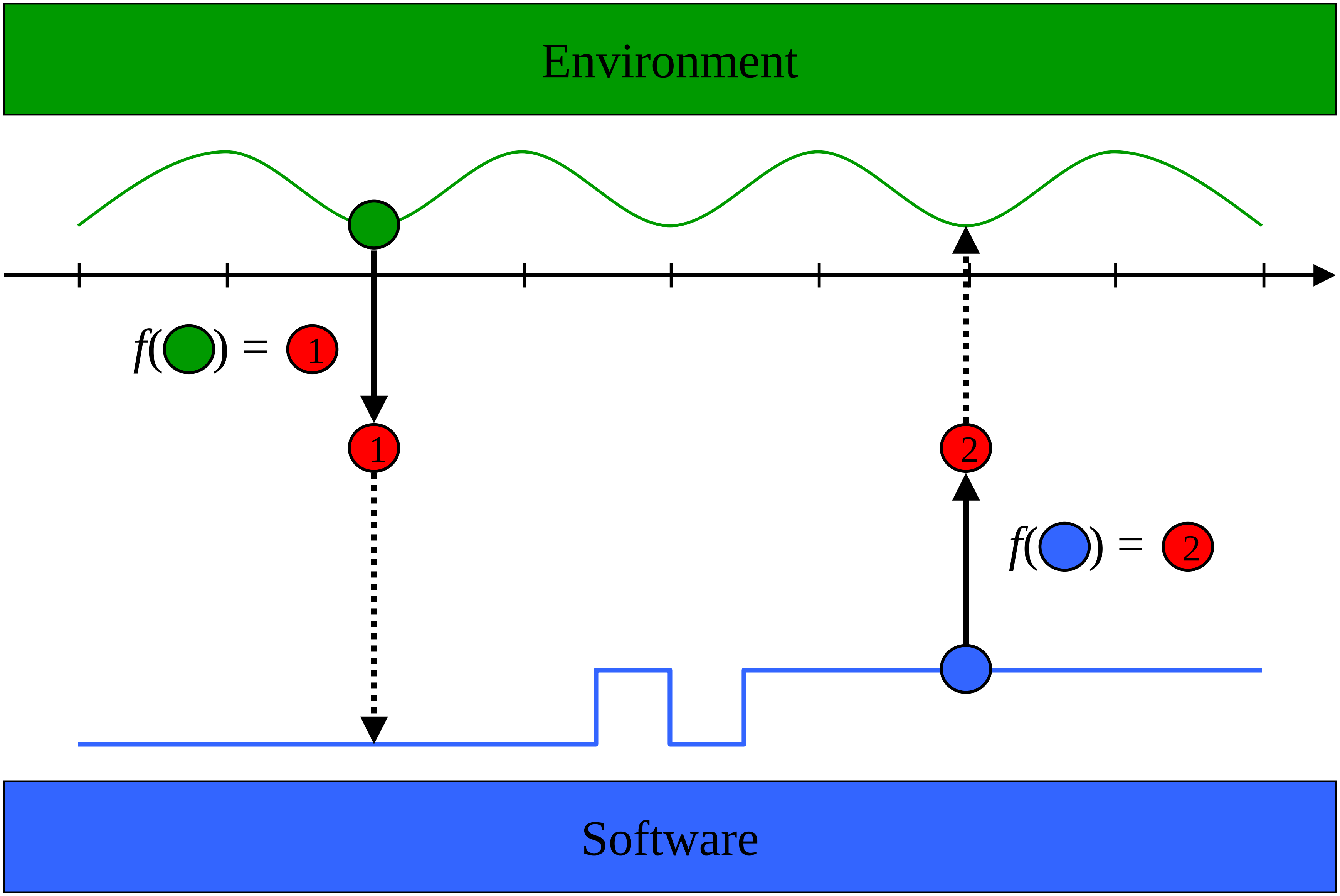
…but Atomic



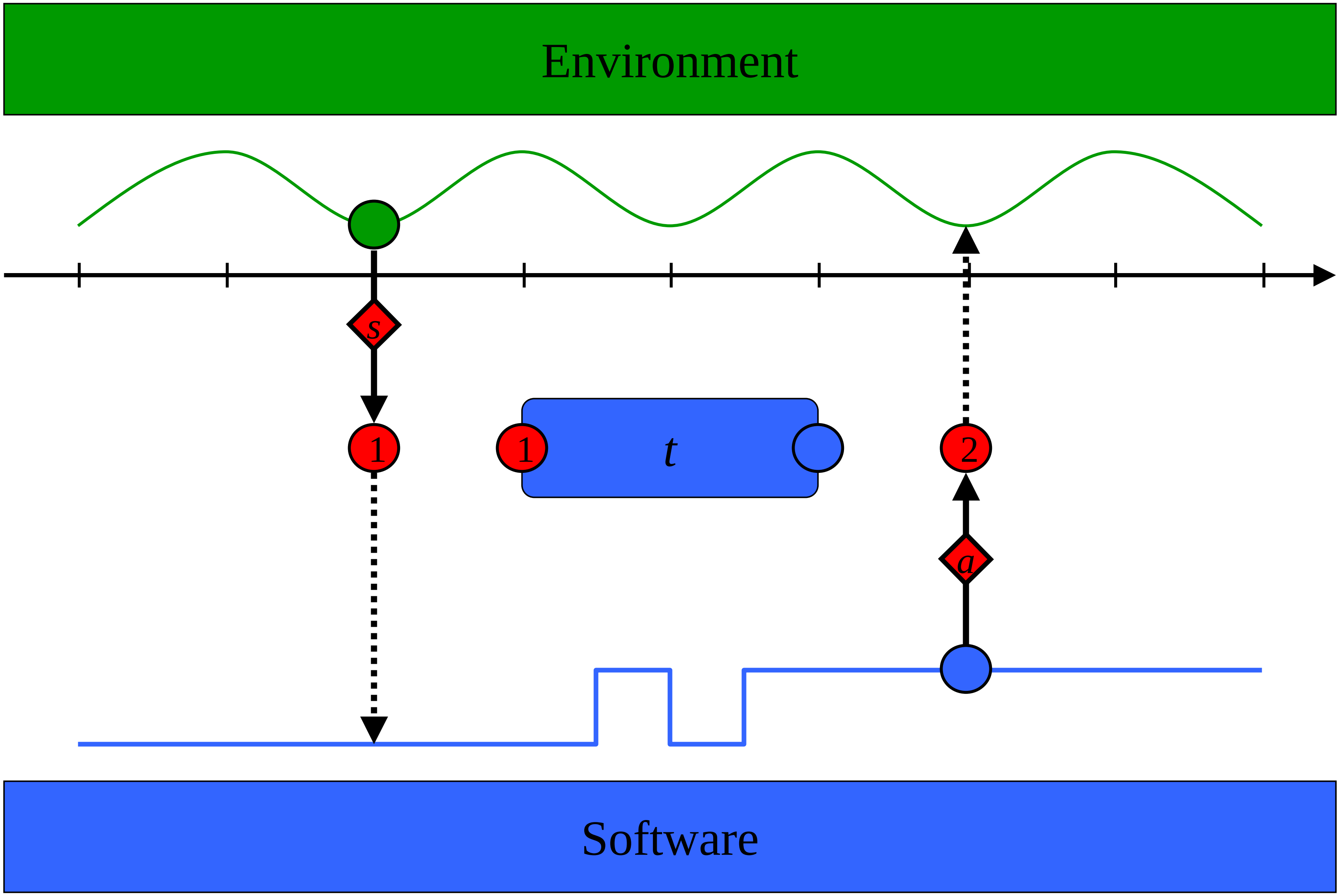
The Driver Model



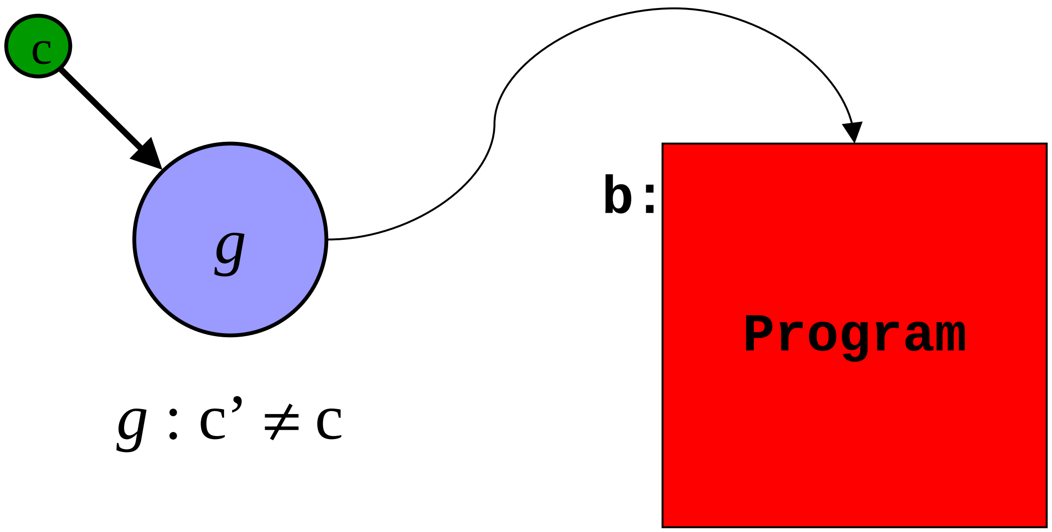
Non-preemptable, Synchronous



Syntax

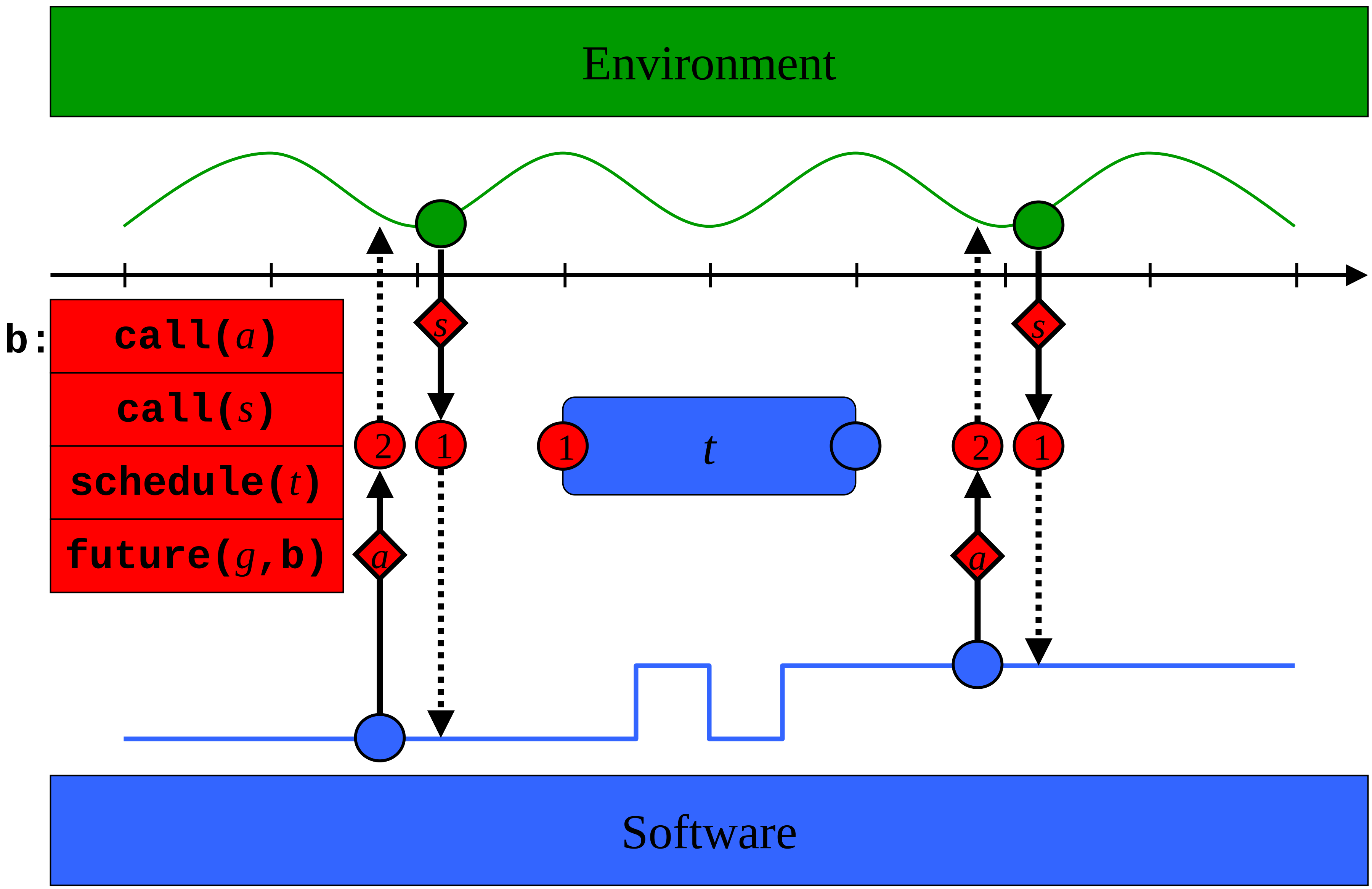


A Trigger *g*

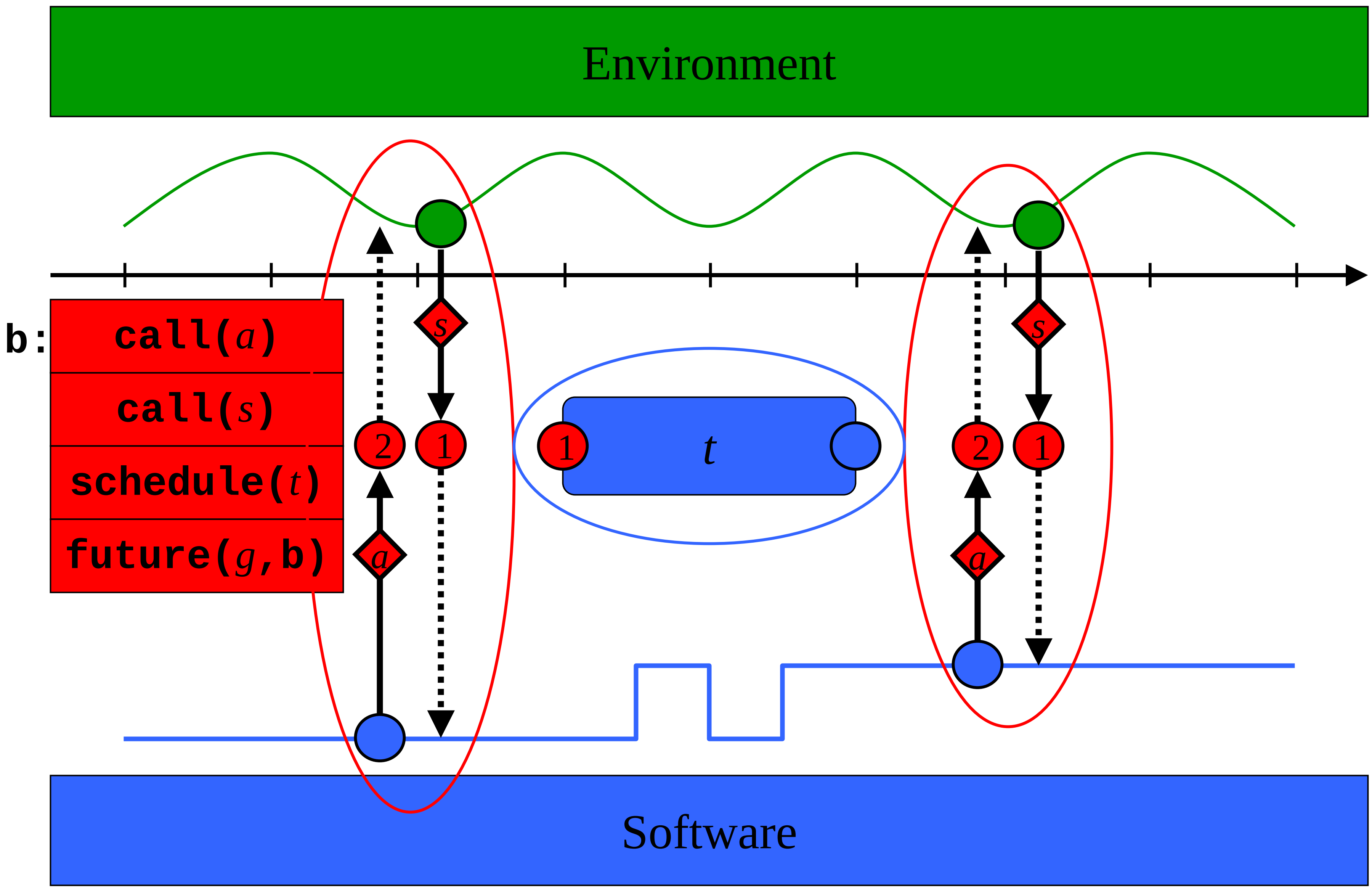


g : c’ ≠ c

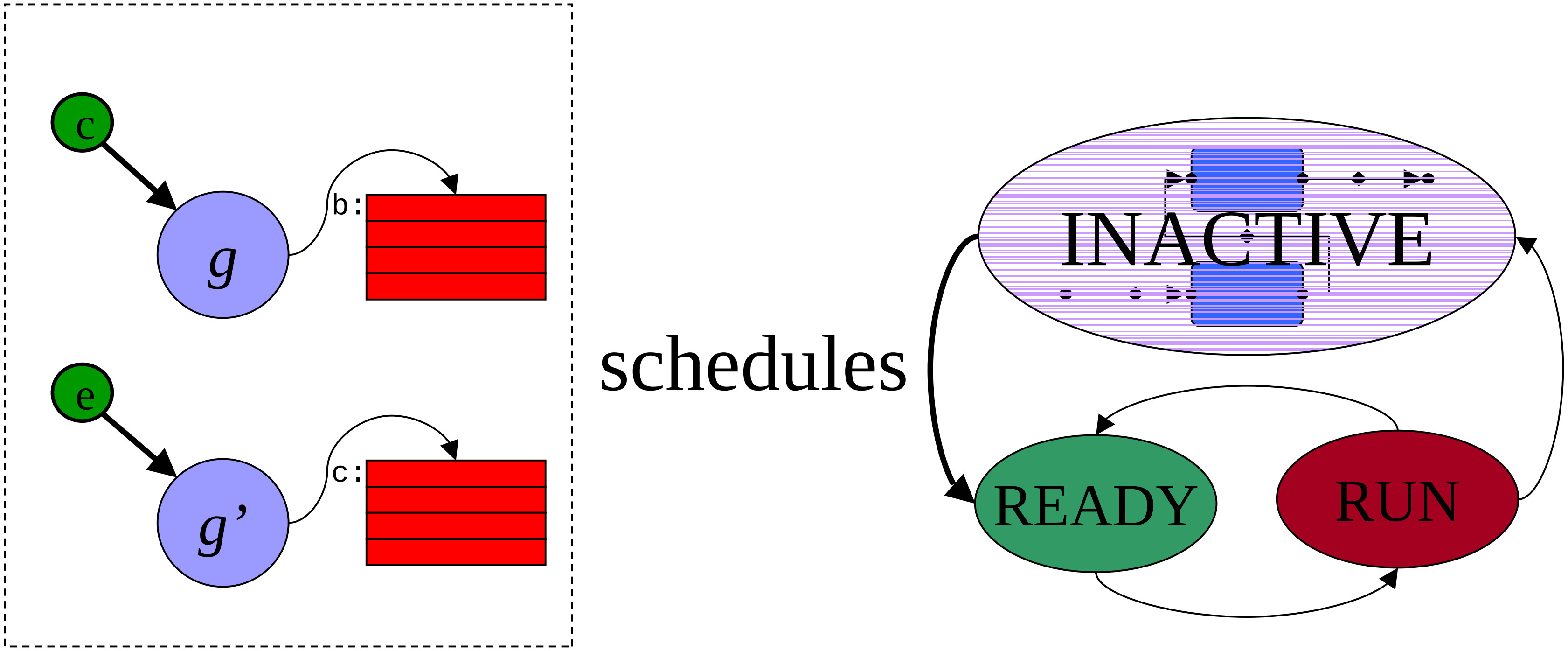
An Embedded Machine Program



Synchronous vs. Scheduled Computation



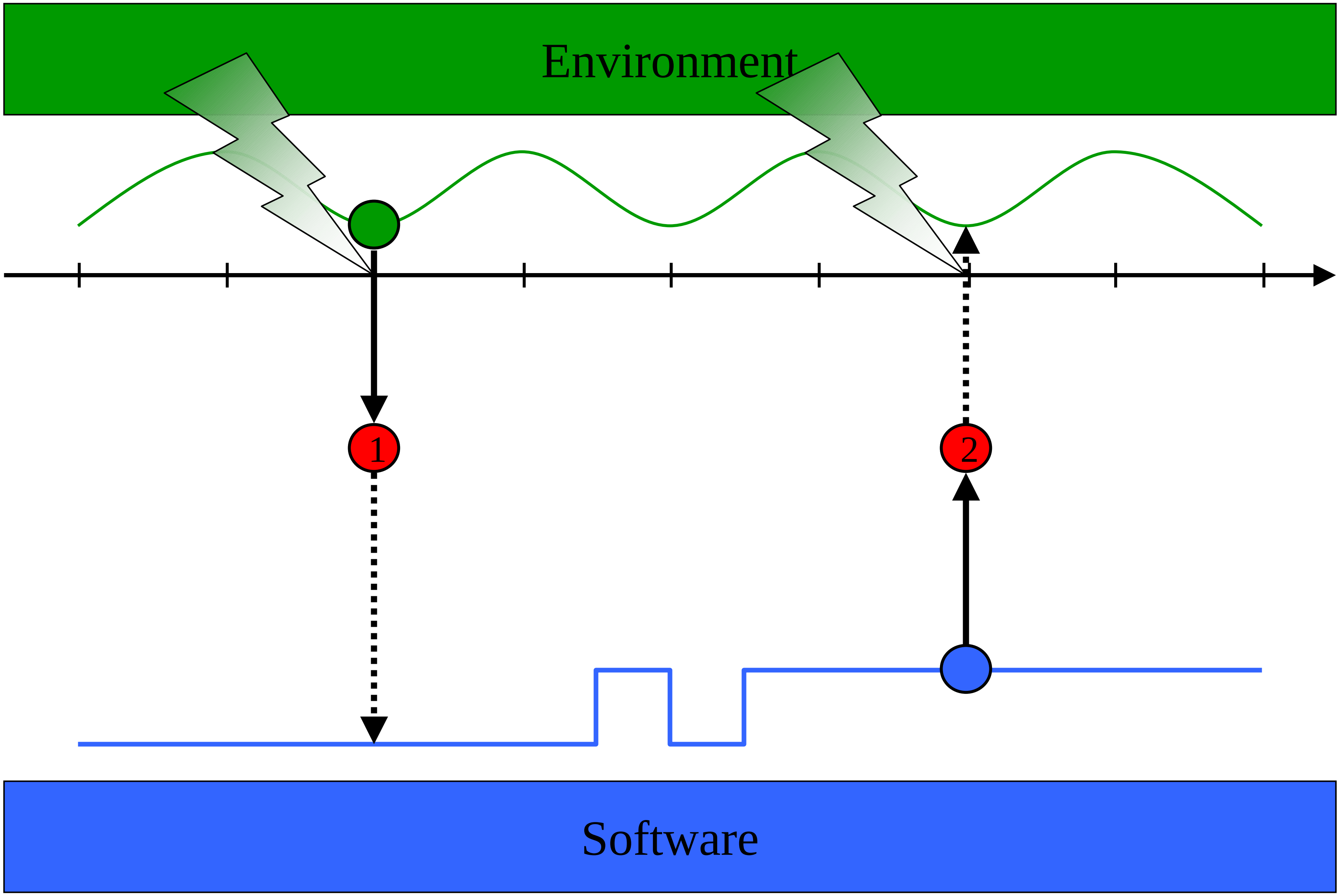
Synchronous vs. Scheduled Computation



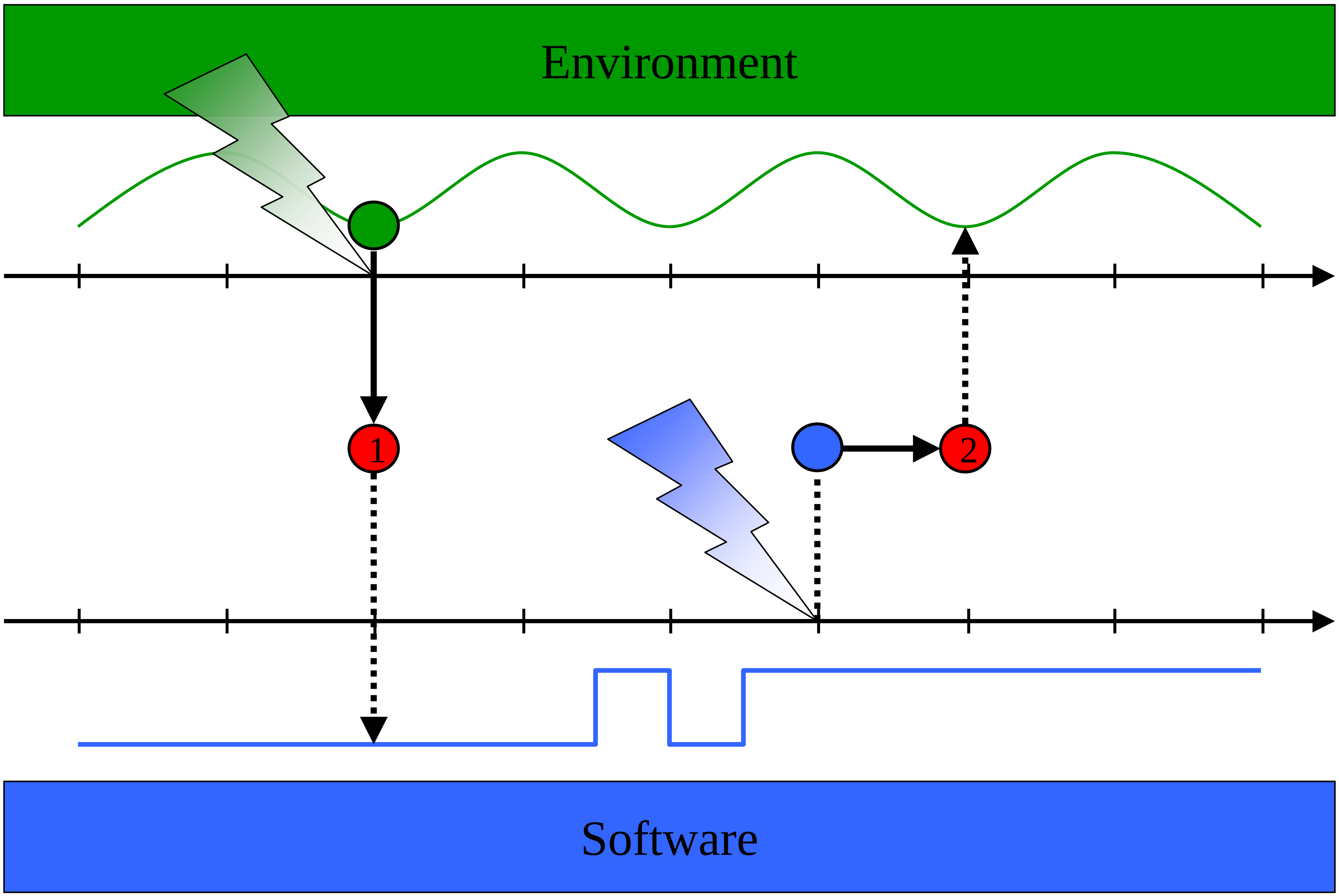
- Synchronous computation
- Kernel context
- Trigger related interrupts disabled

- Scheduled computation
- User context

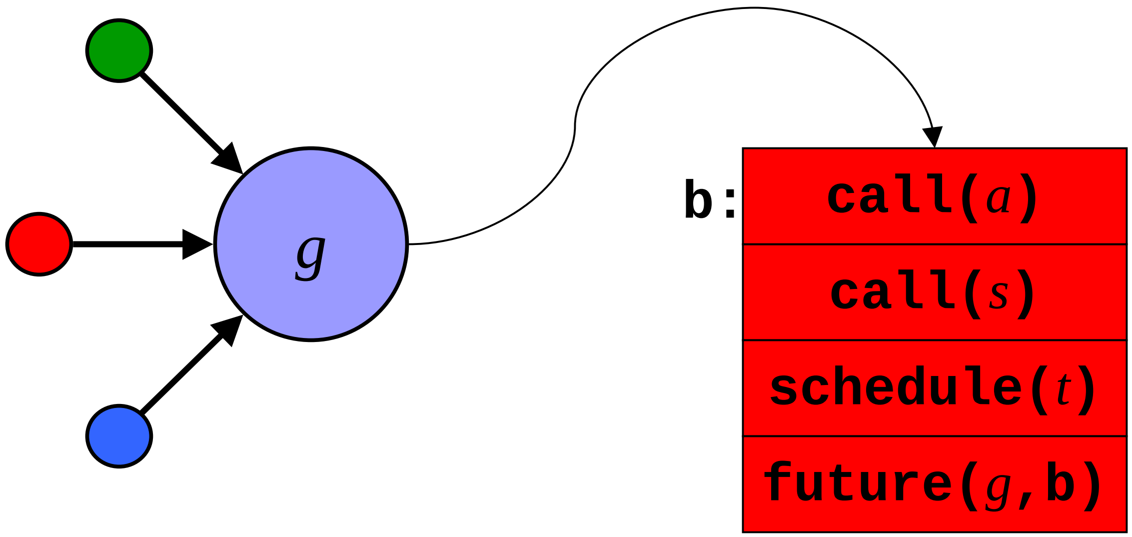
Environment-triggered Code



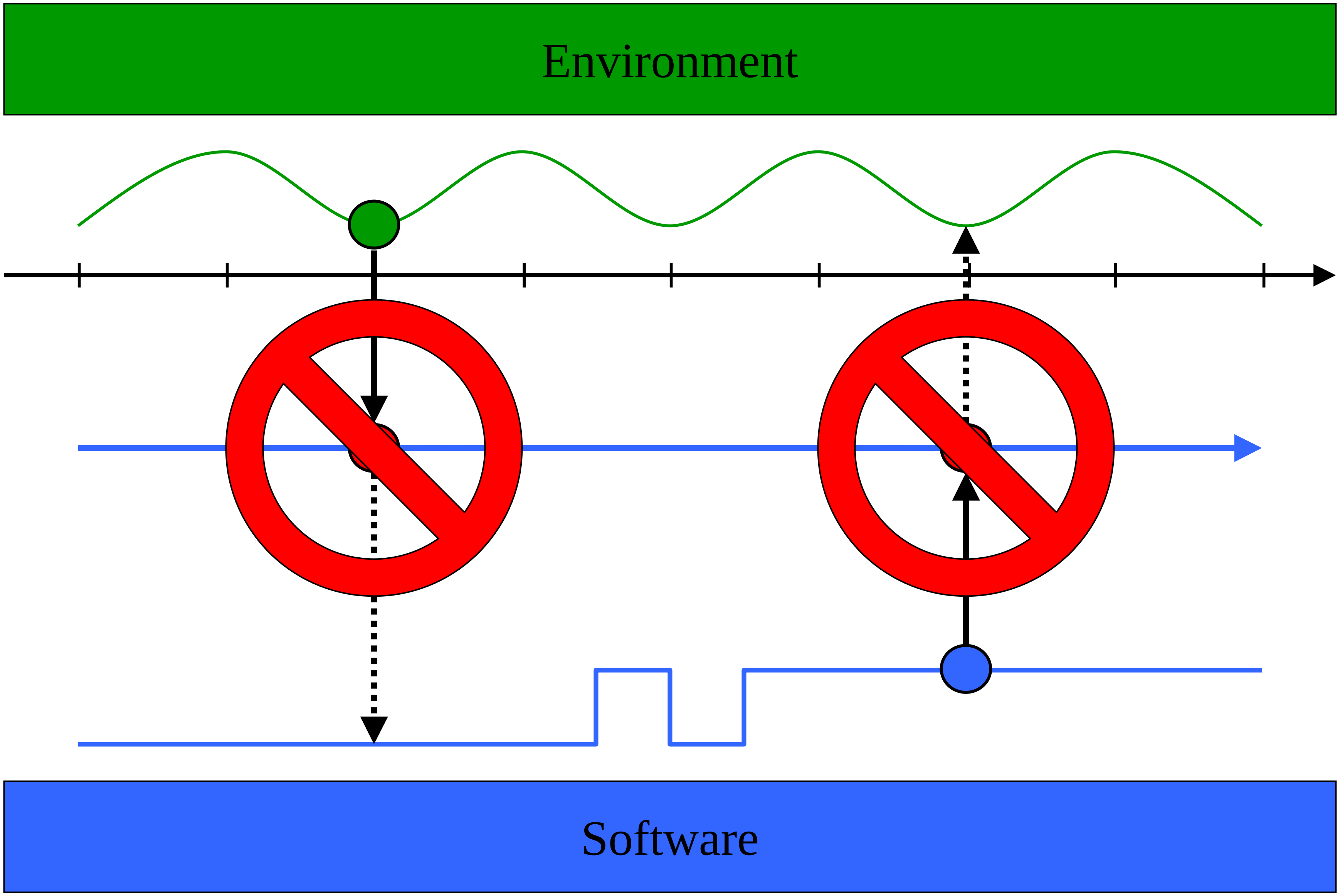
Software-triggered Code



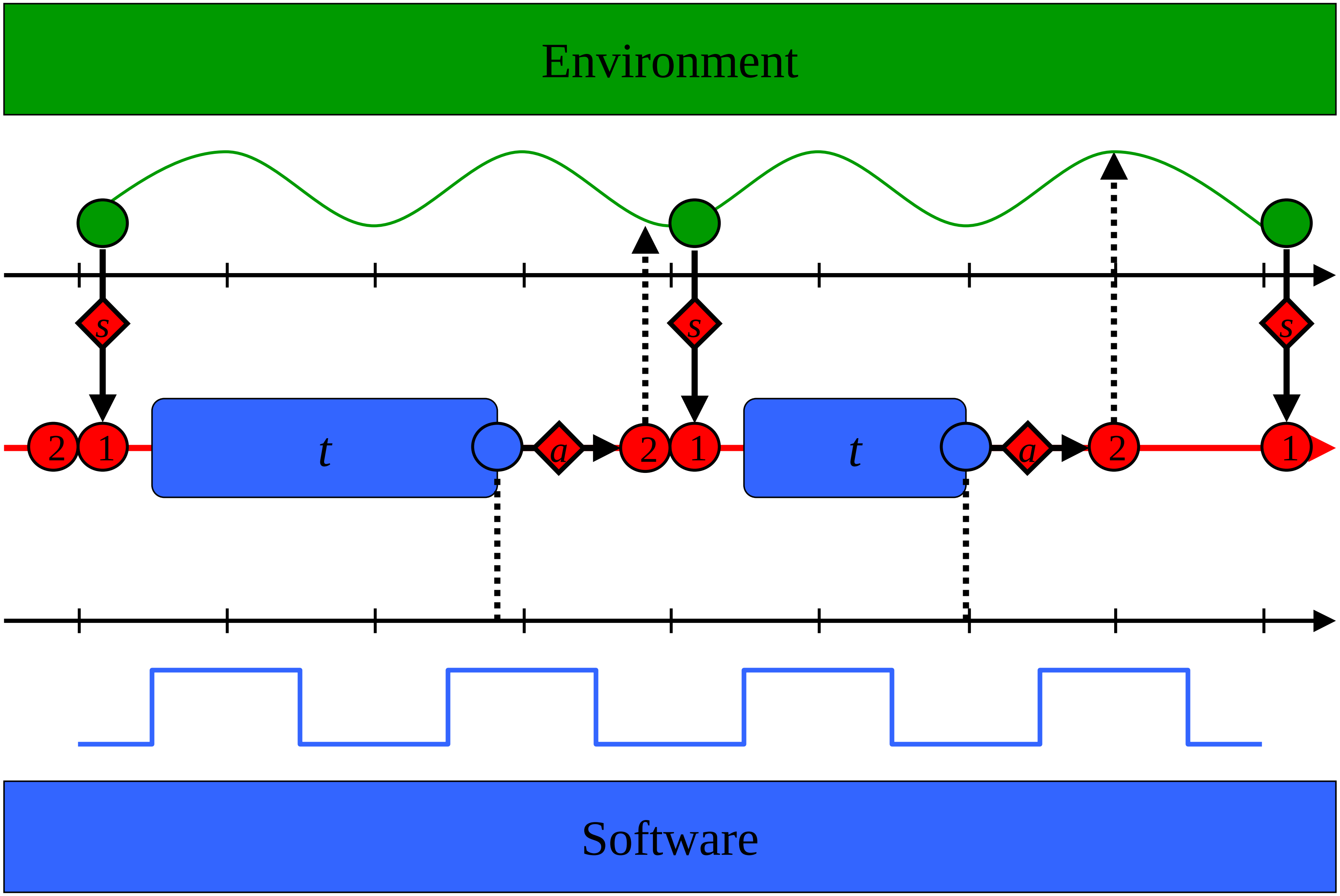
Trigger *g*: Input-, Environment-Triggered



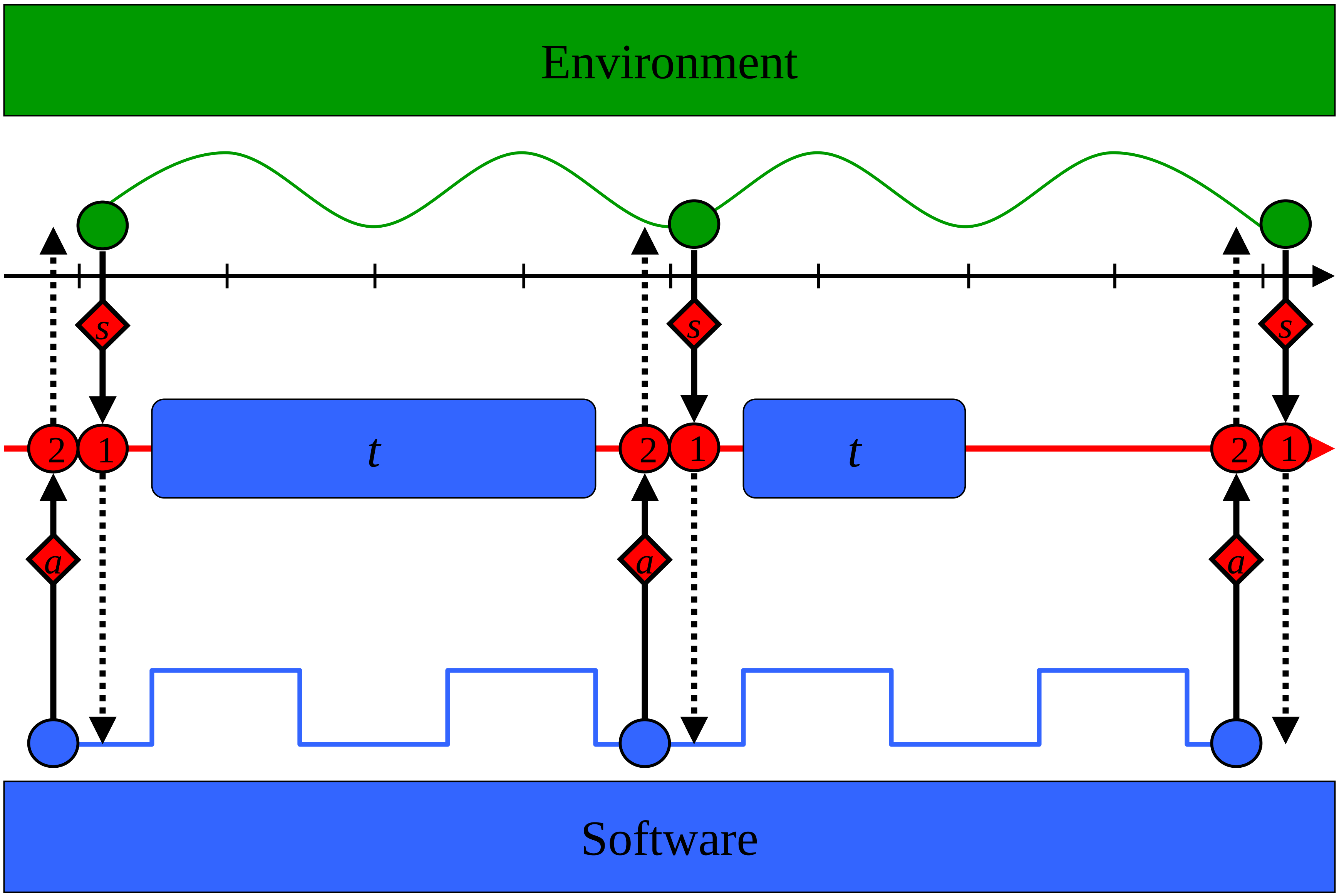
Time Safety



Input-deterministic If Time Safe

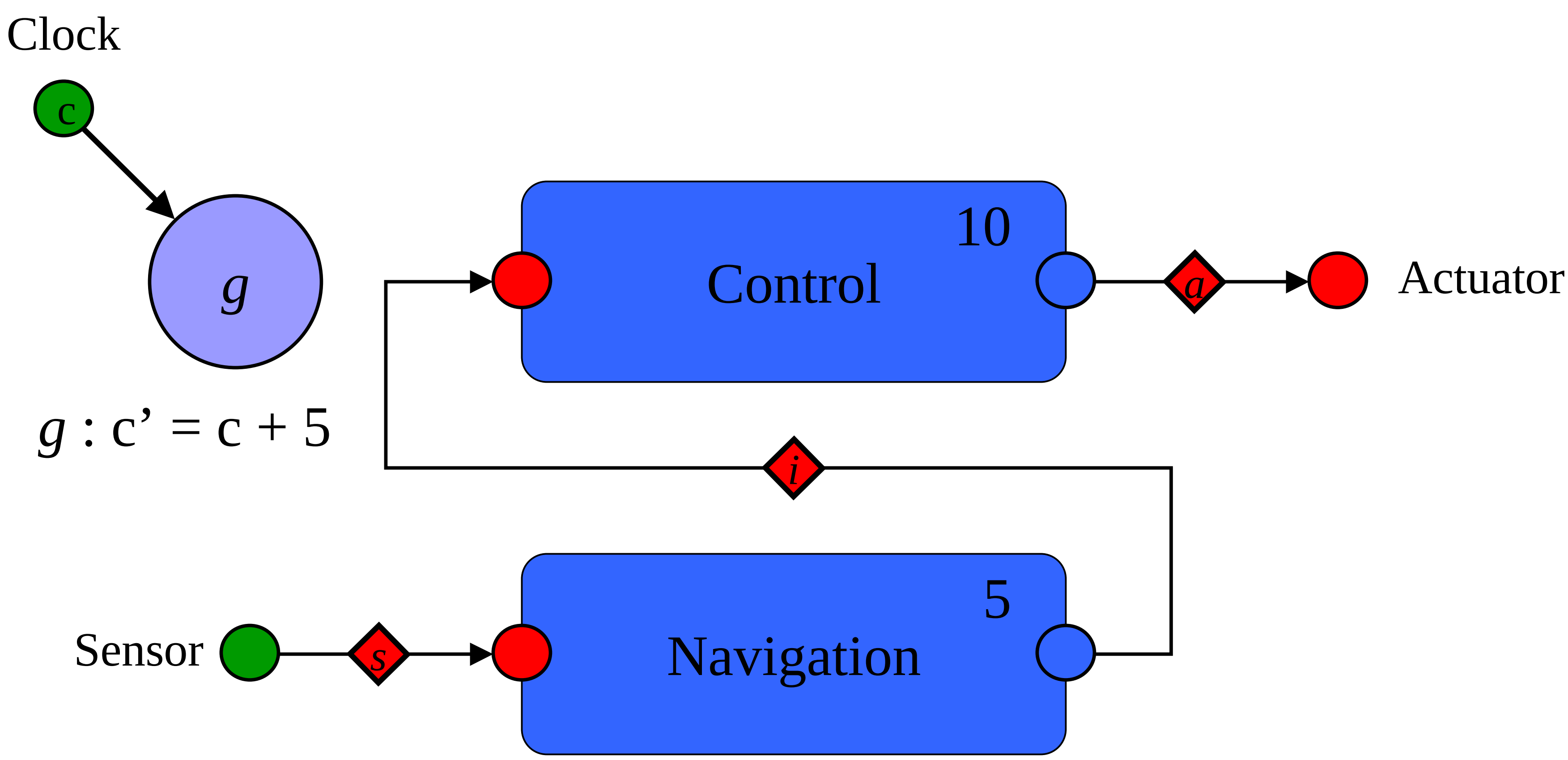


Environment-deterministic If Environment-triggered

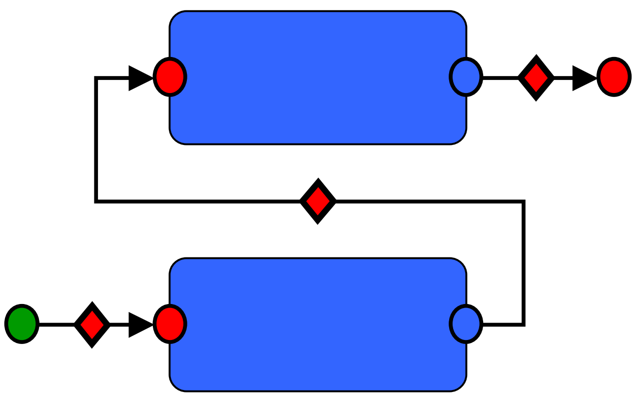


The Zürich Helicopter

Helicopter Control Software

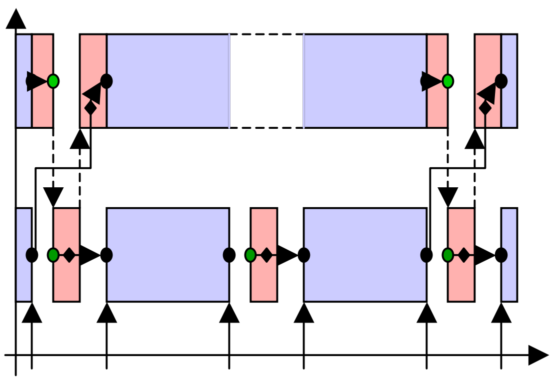


Giotto Syntax (Functionality)



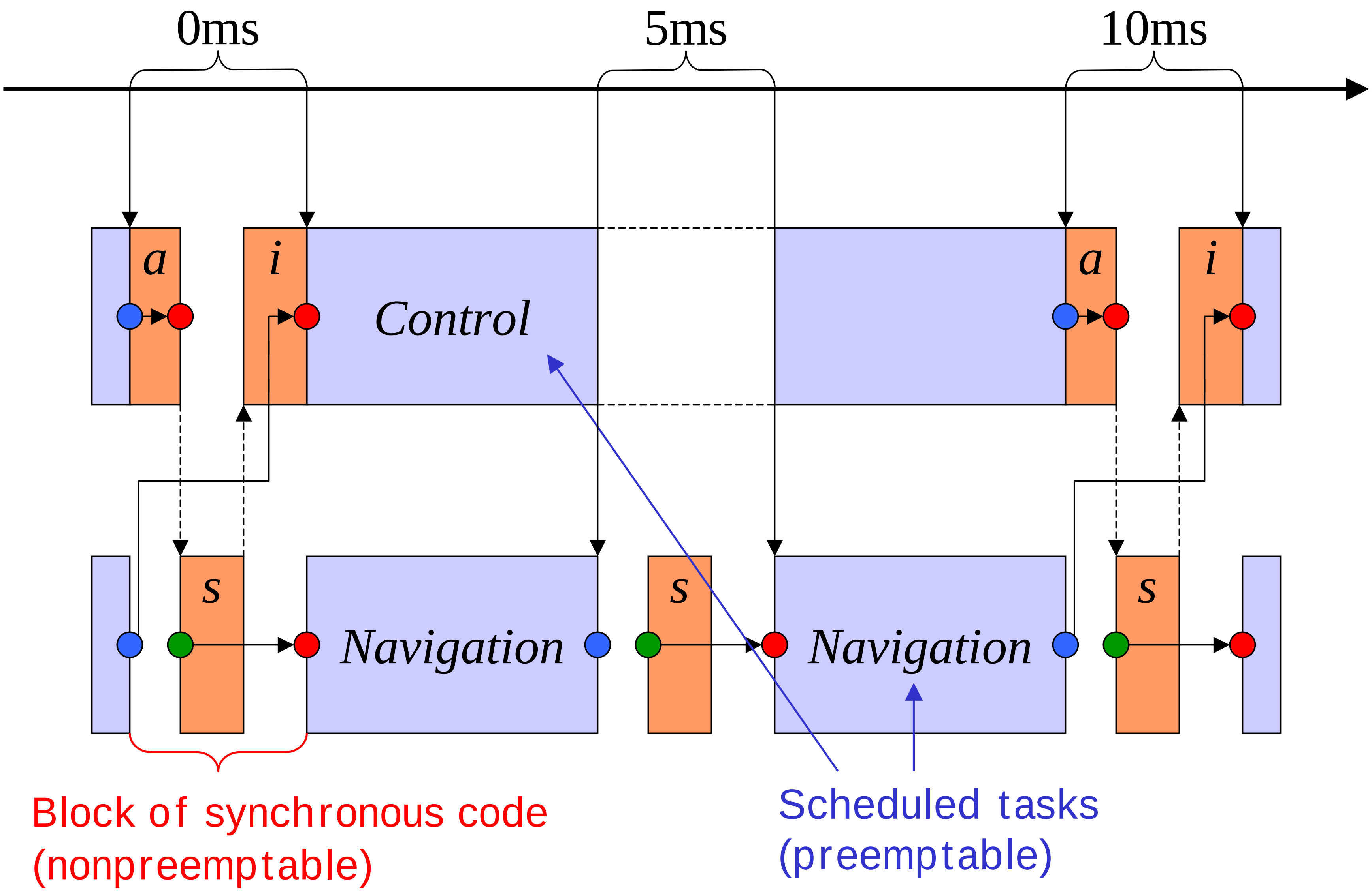
```
sensor gps_type GPS uses c_gps_device ;

actuator servo_type Servo := c_servo_init
         uses c_servo_device ;

output

ctr_type CtrOutput := c_ctr_init ;

nav_type NavOutput := c_nav_init ;


driver sensing (GPS) output (gps_type gps)
{ c_gps_pre_processing ( GPS, gps ) }


task Navigation (gps_type gps) output (NavOutput)
{ c_matlab_navigation_code ( gps, NavOutput ) }

...
```

Giotto Syntax (Timing)

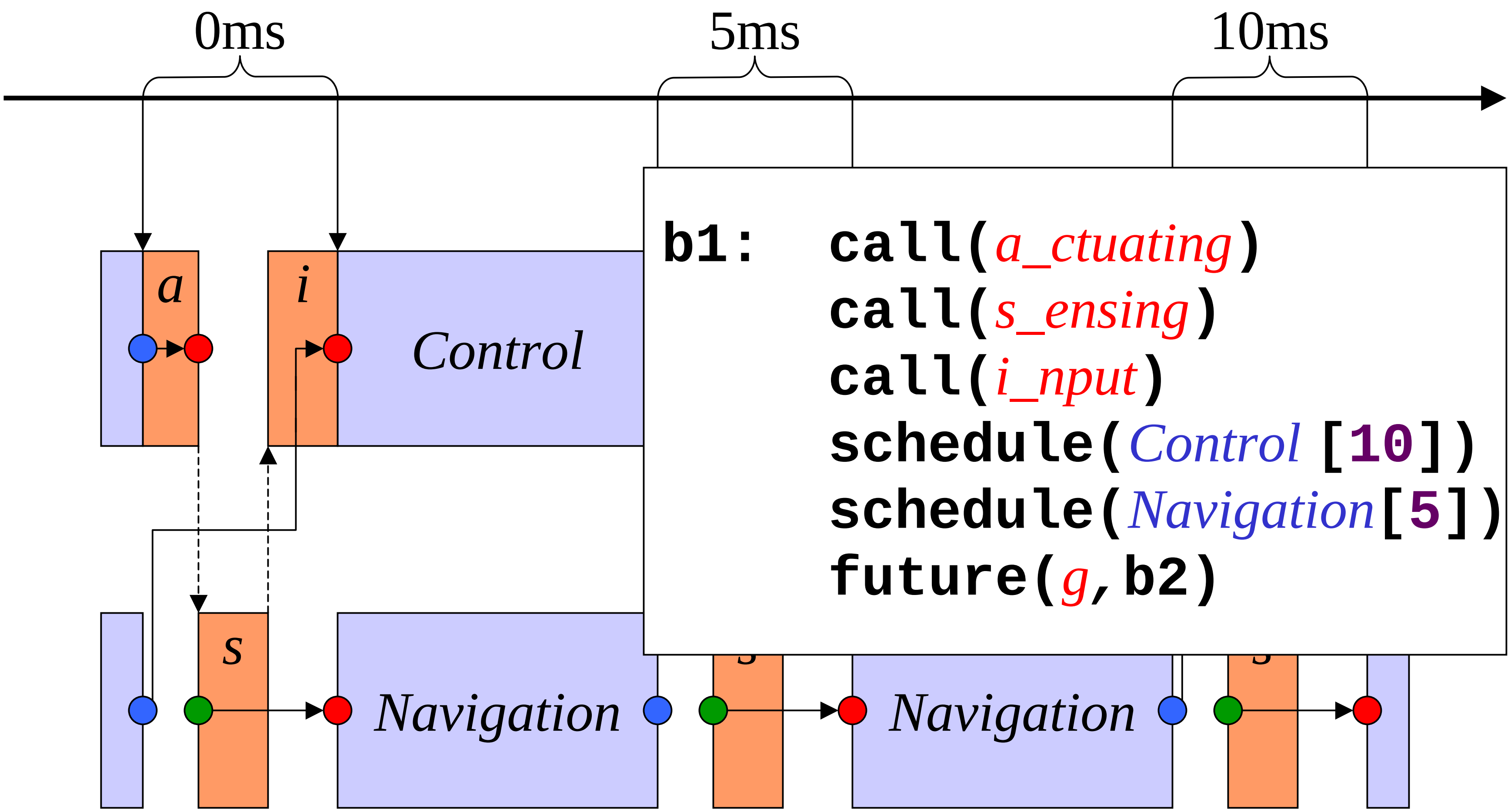


```
...
mode Flight ( ) period 10ms
   {
      actfreq 1 do Servo ( actuating ) ;

      taskfreq 1 do Control ( input ) ;
      taskfreq 2 do Navigation ( sensing ) ;
   }
...
```

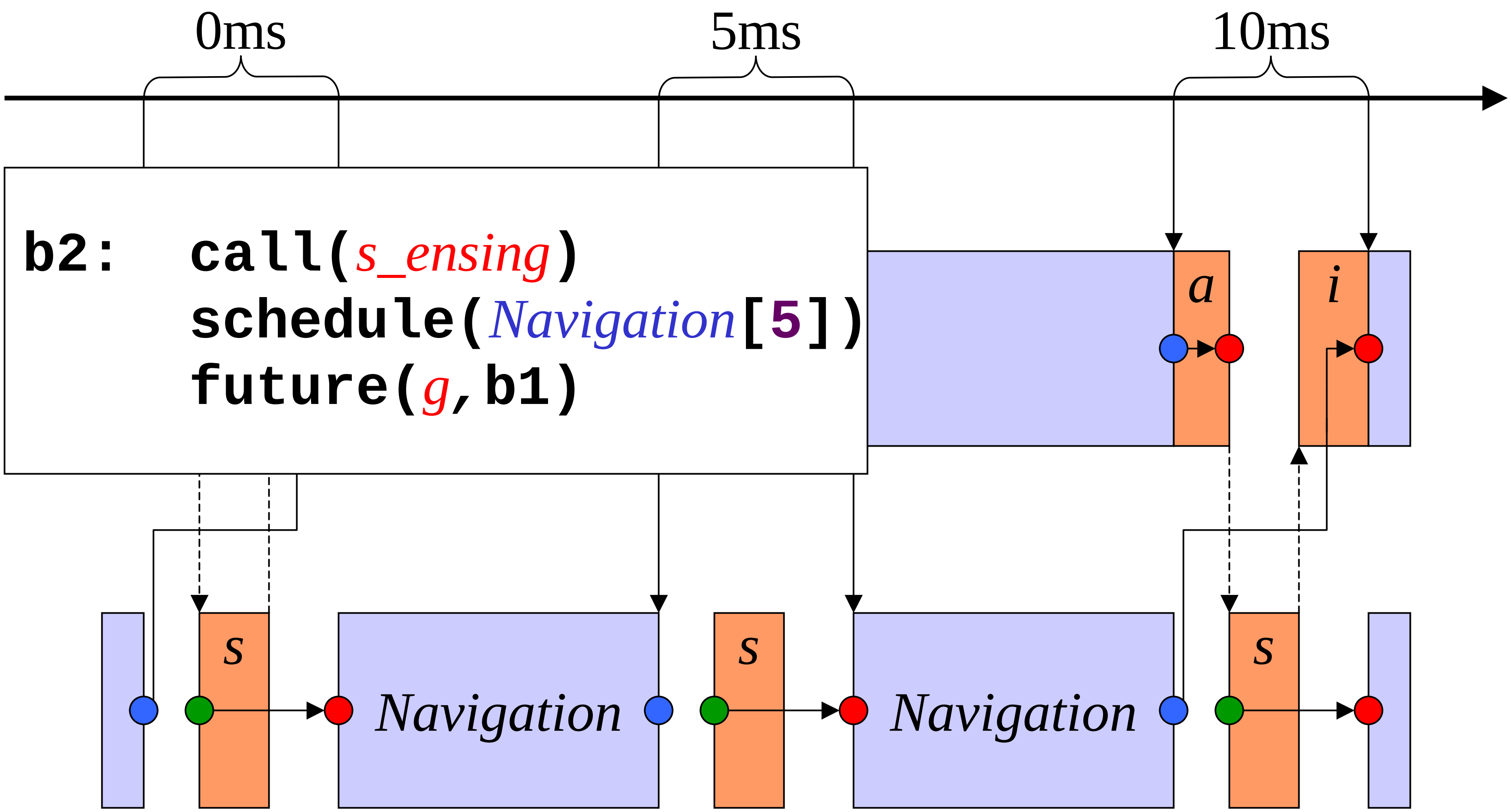
Environment Timeline



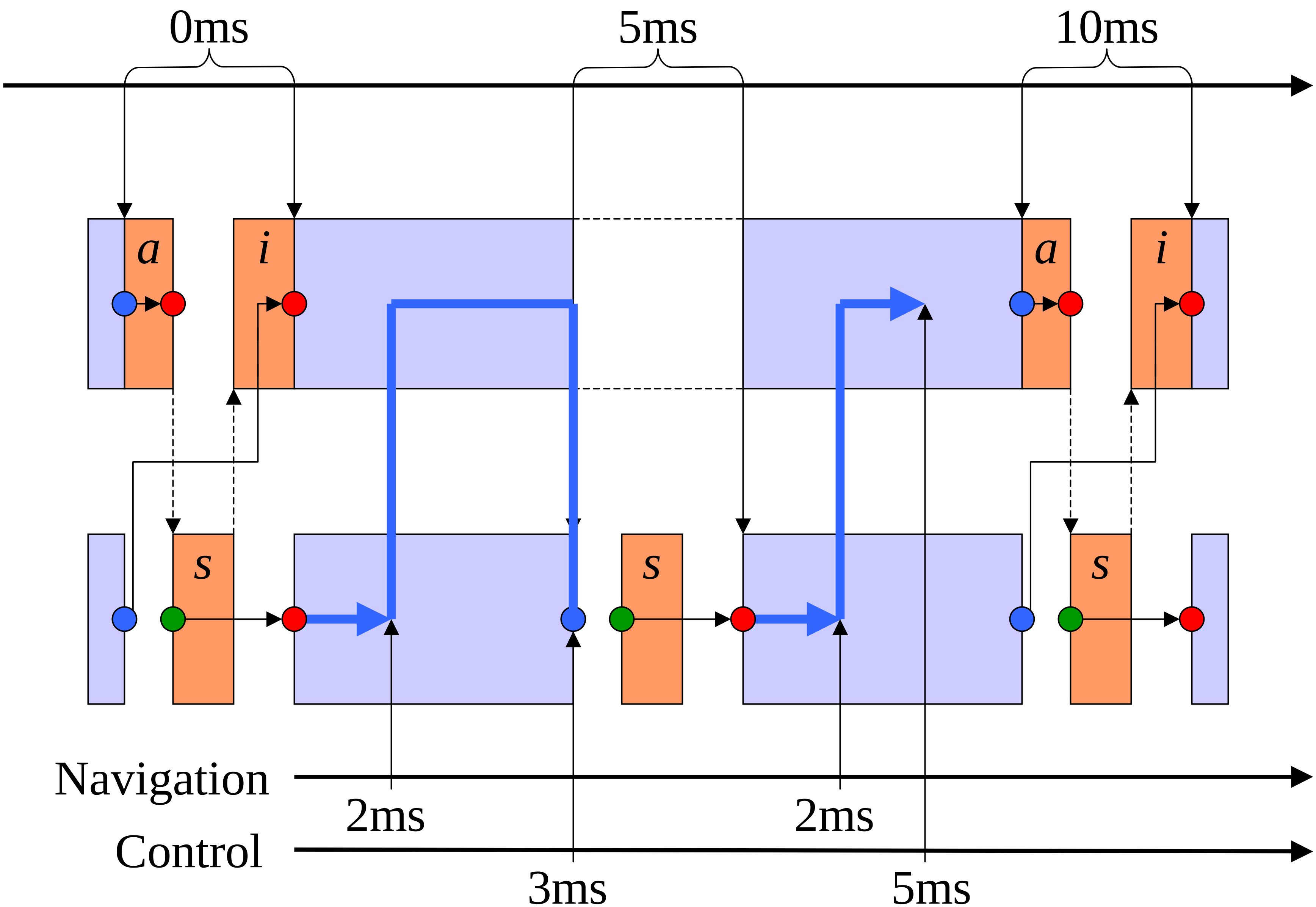
E Code


0ms
5ms
10ms
a
i
Control
s
Navigation
Navigation
b1: call(a_ctuating)
call(s_ensing)
call(i_nput)
schedule(Control [10])
schedule(Navigation[5])
future(g,b2)

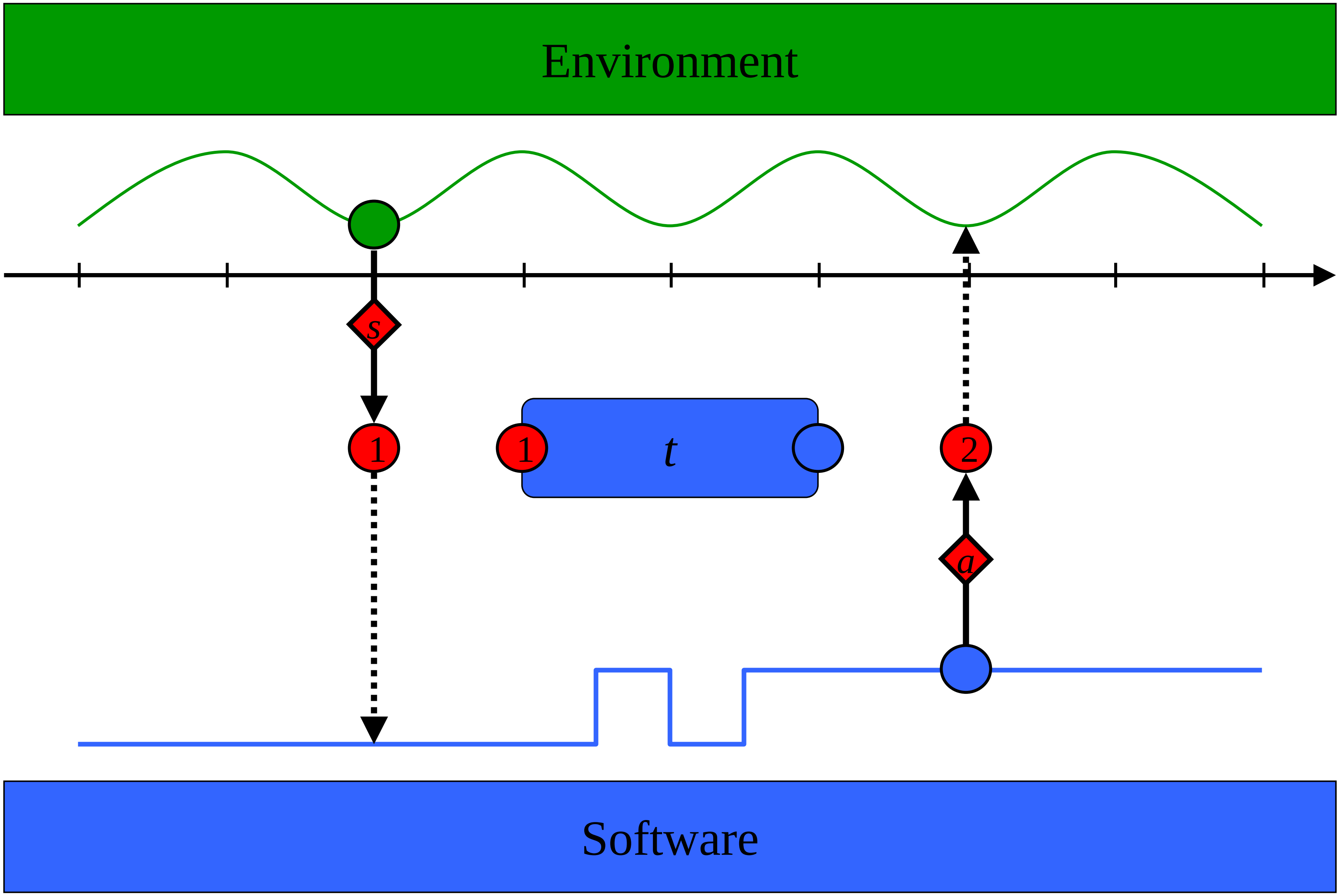
E Code


0ms
5ms
10ms
b2: call(s_ensing)
schedule(Navigation[5])
future(g,b1)
a
i
s
Navigation
s
Navigation
s

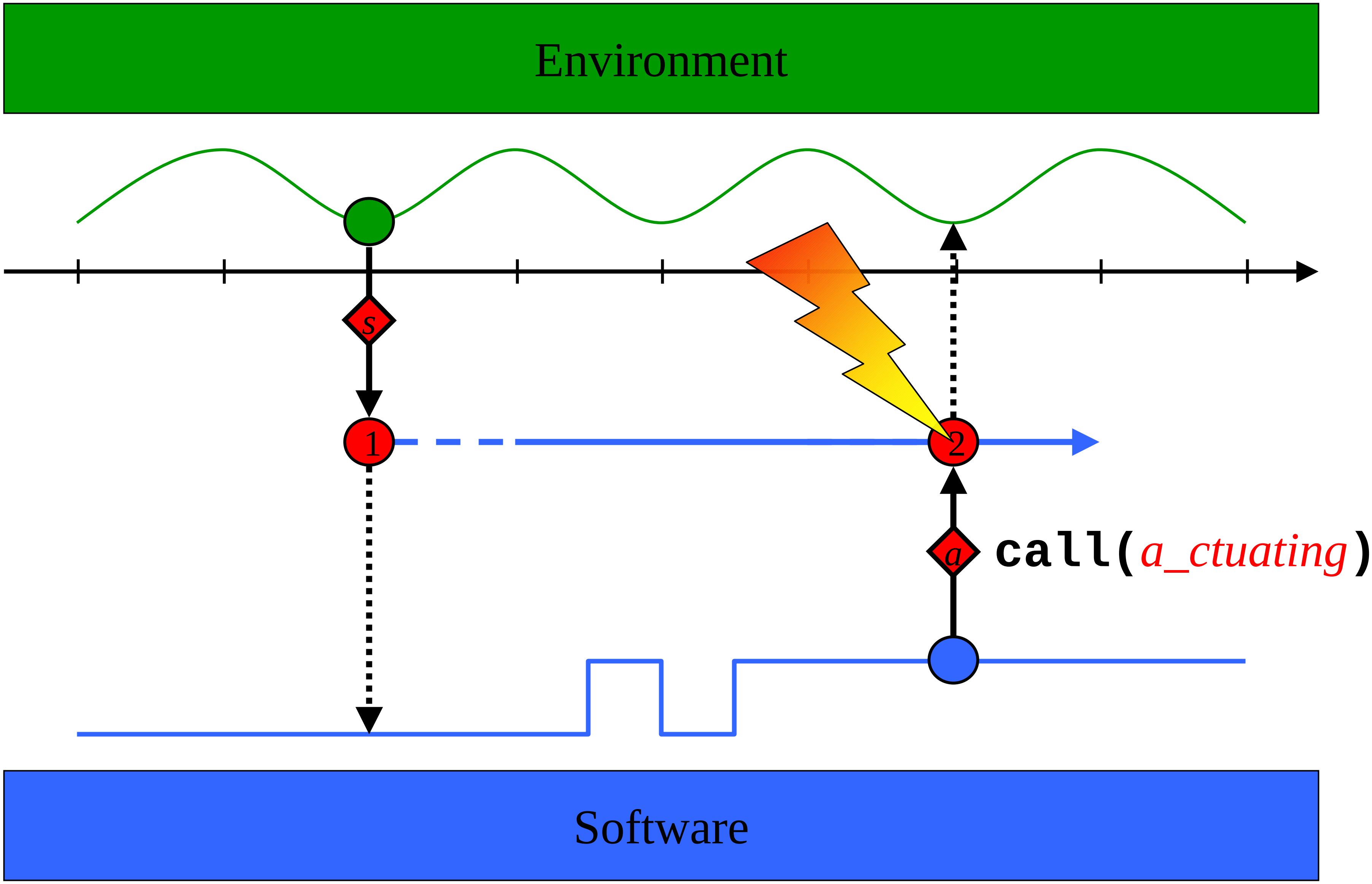
Platform Timeline: EDF



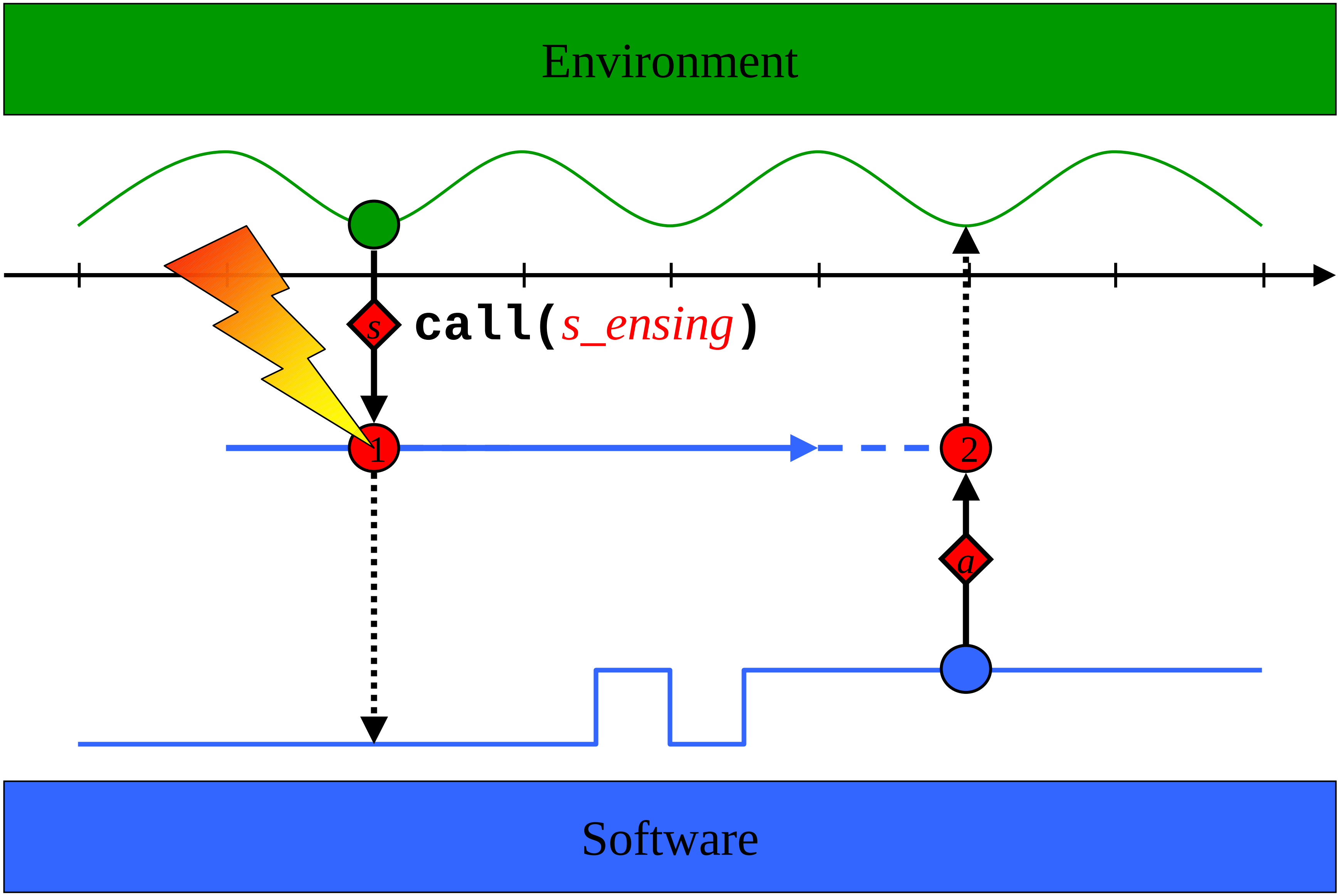
Time Safety



Runtime Exceptions I



Runtime Exceptions II



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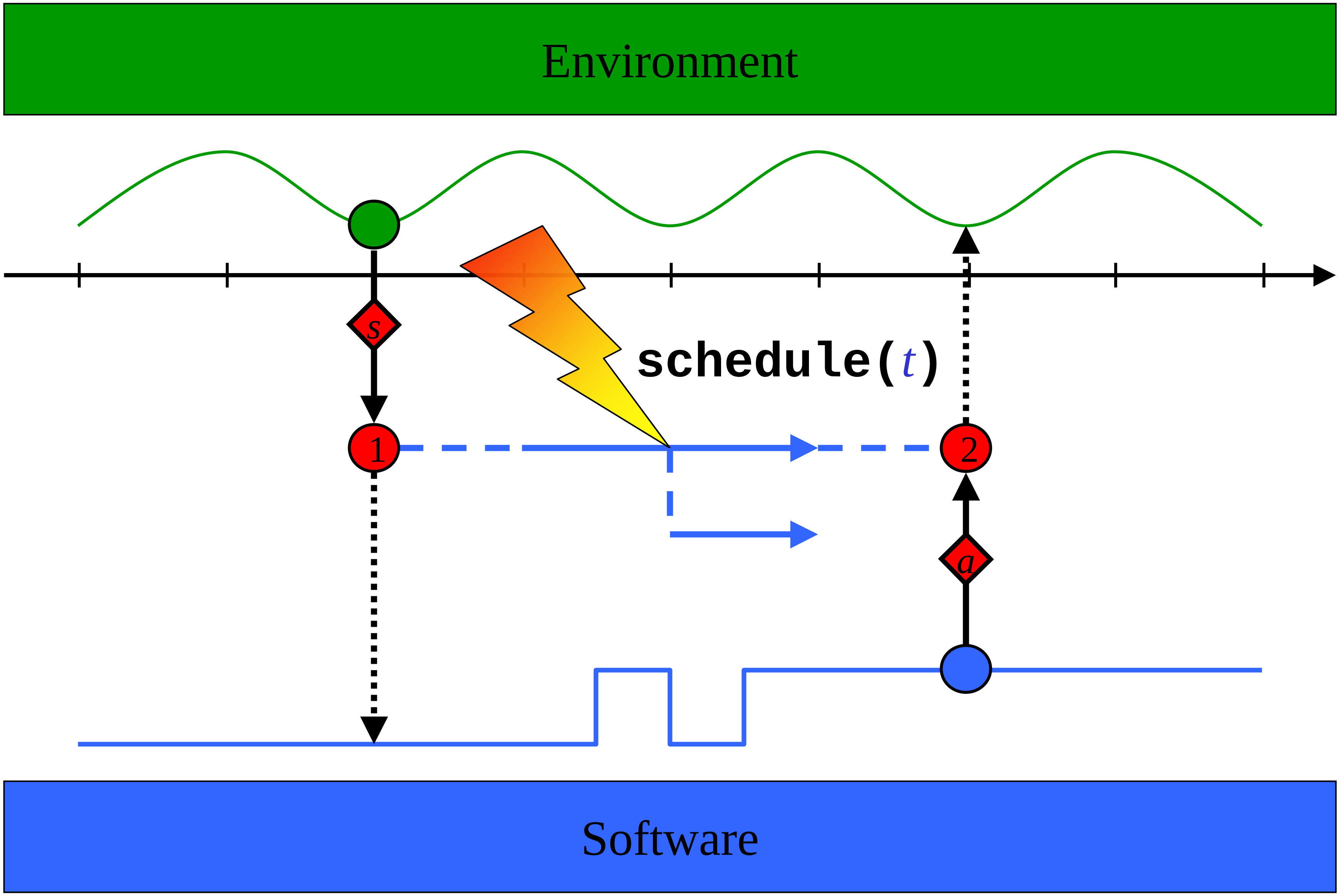
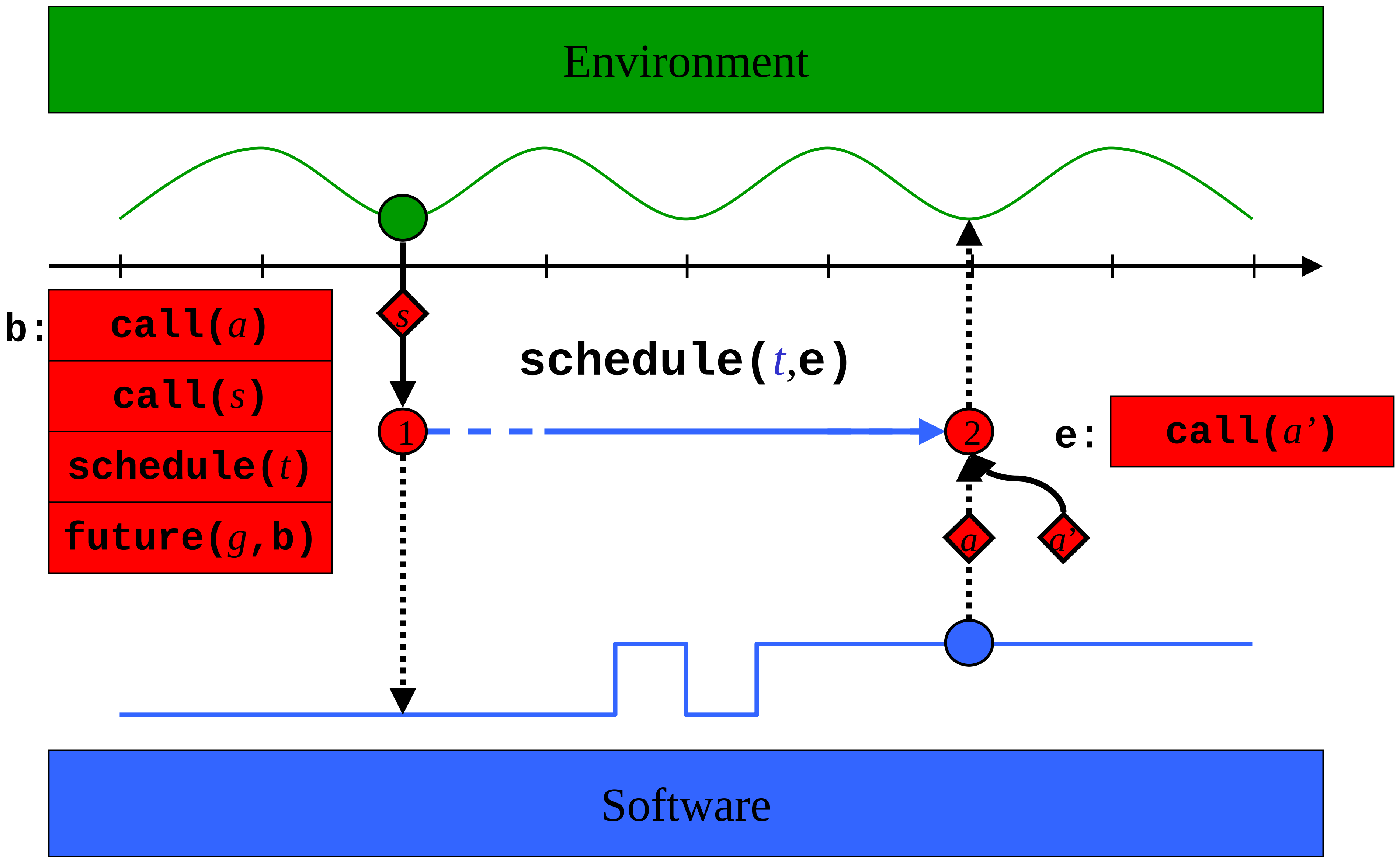
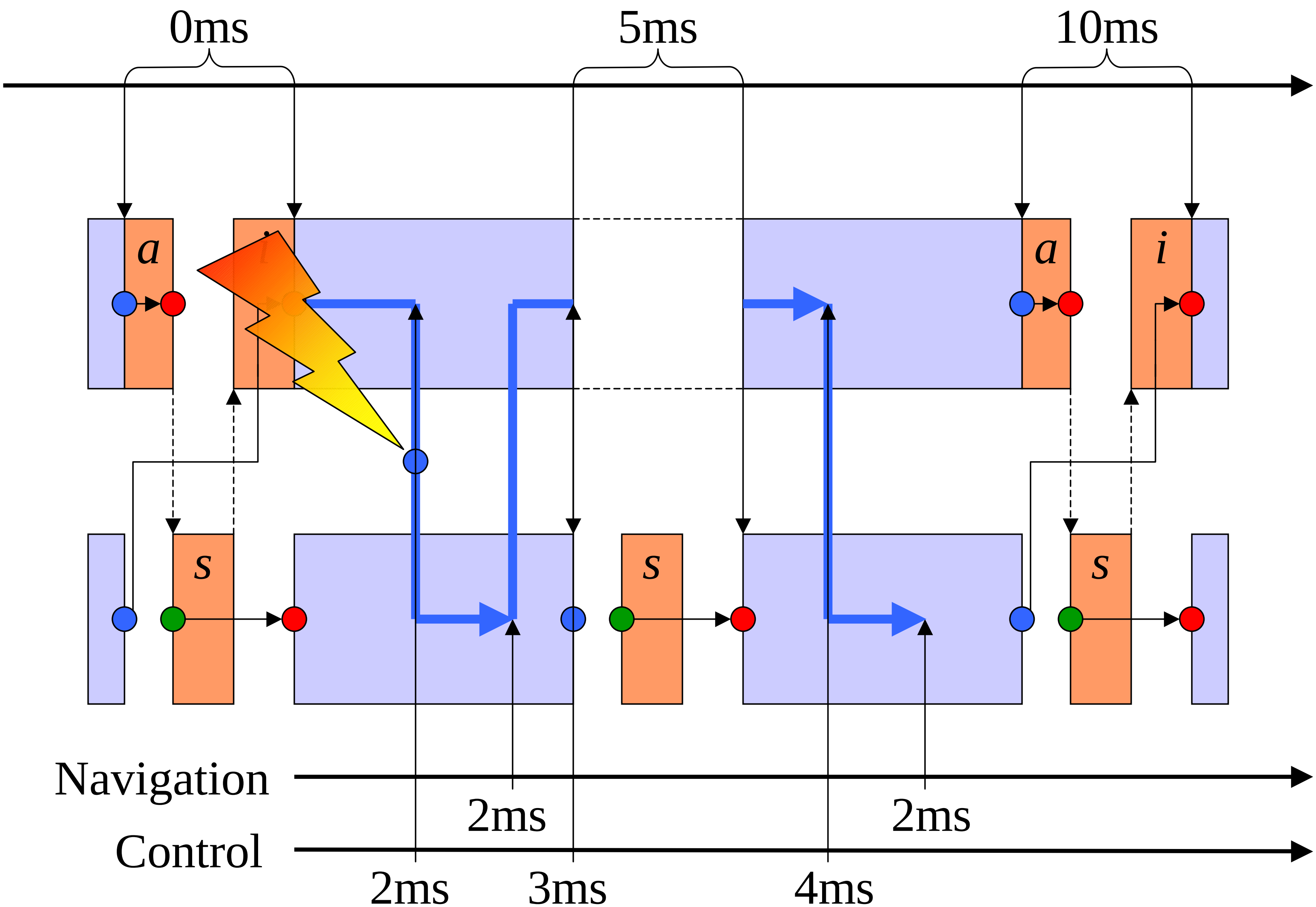
Runtime Exceptions III



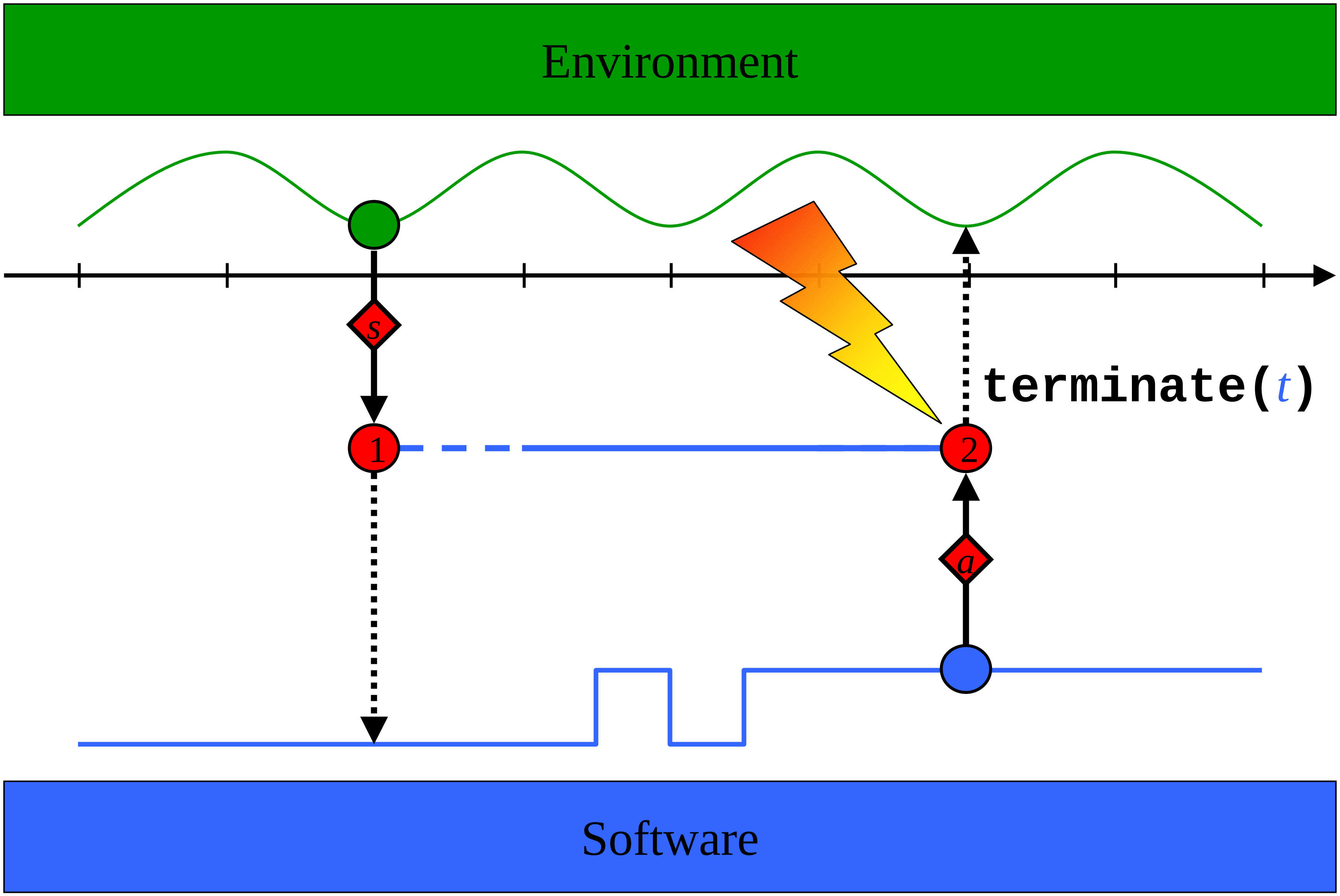
An Exception Handler **e**



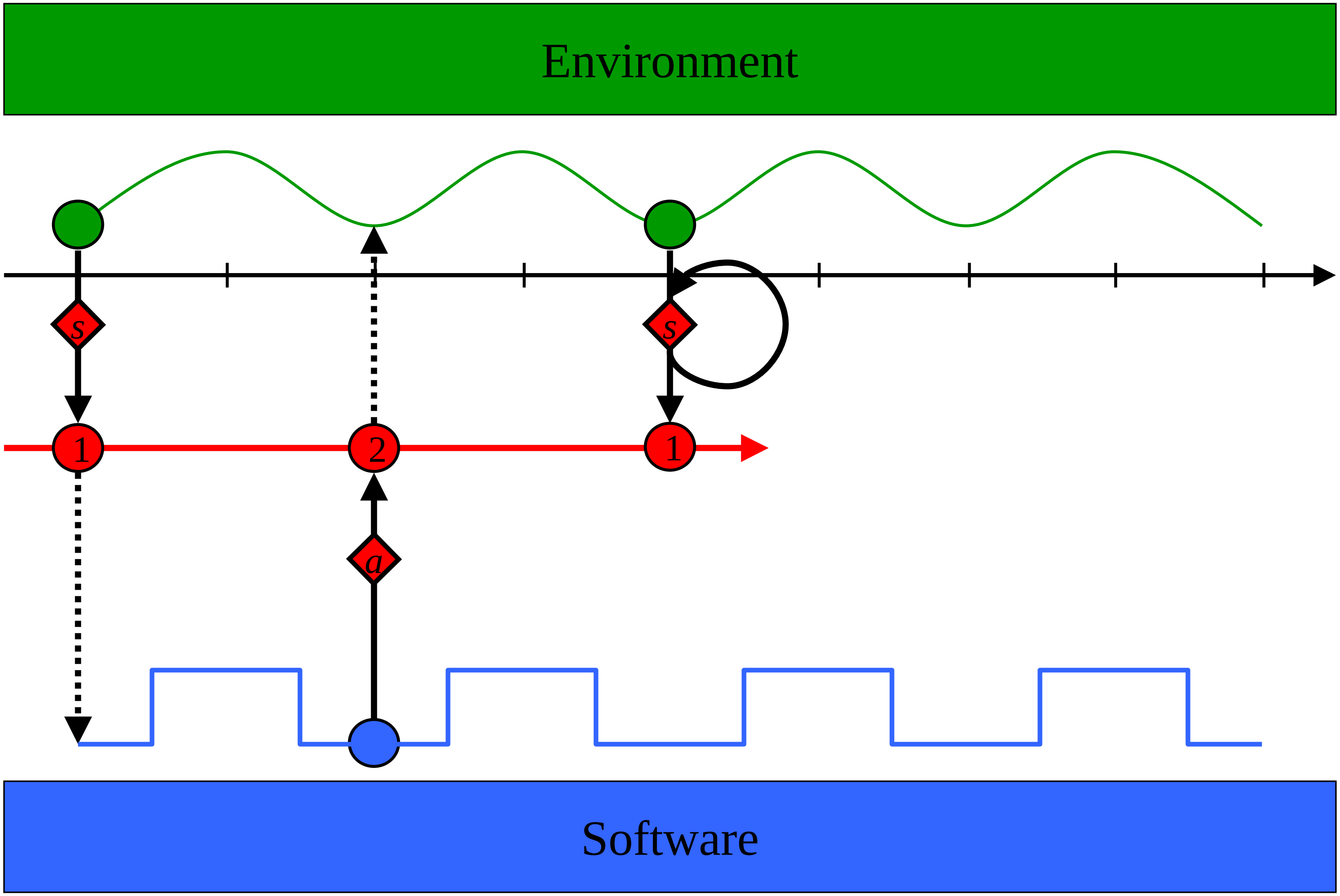
How to Loose Determinism: Task Synchronization



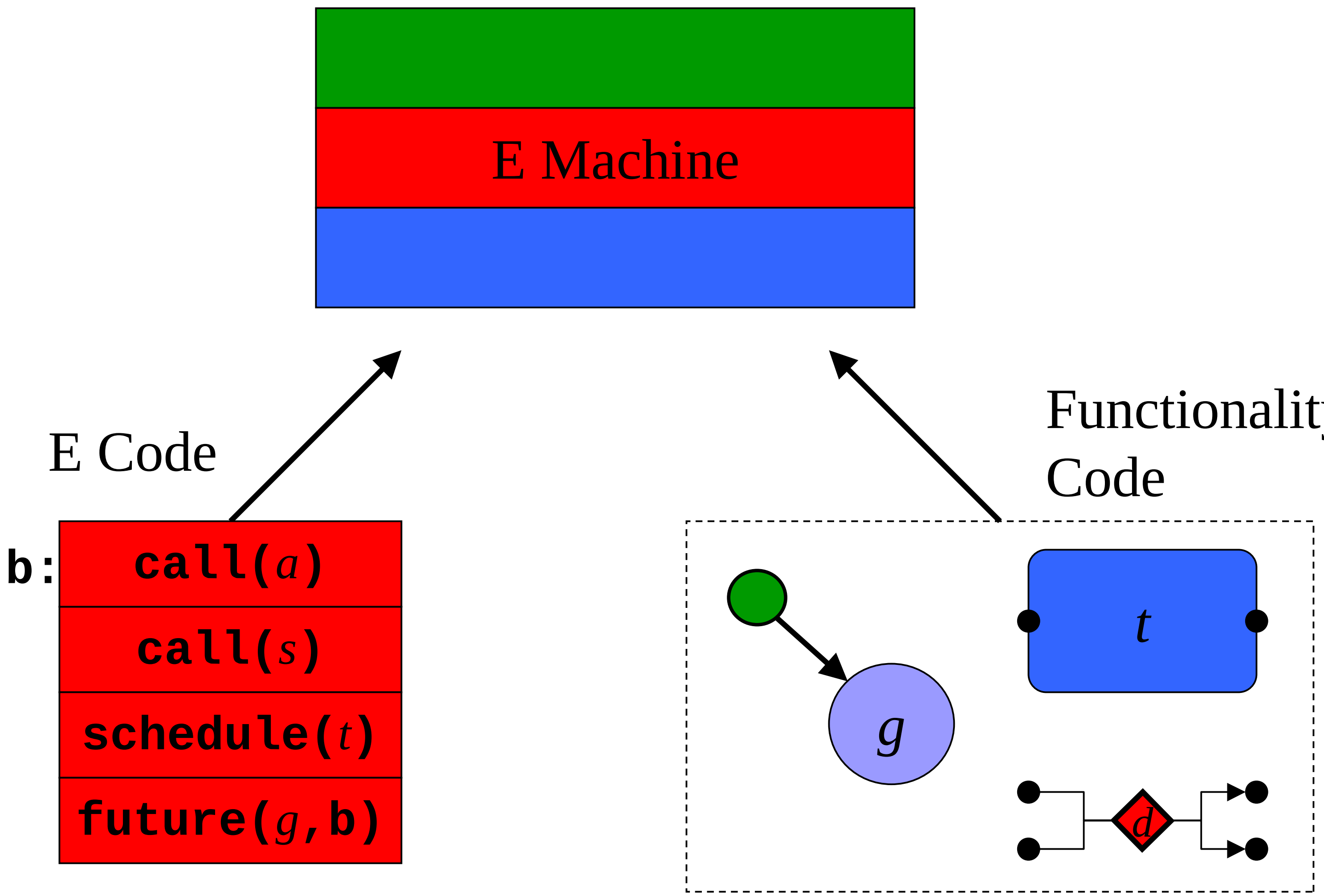
How to Loose Determinism: Termination



Time Liveness: Infinite Traces

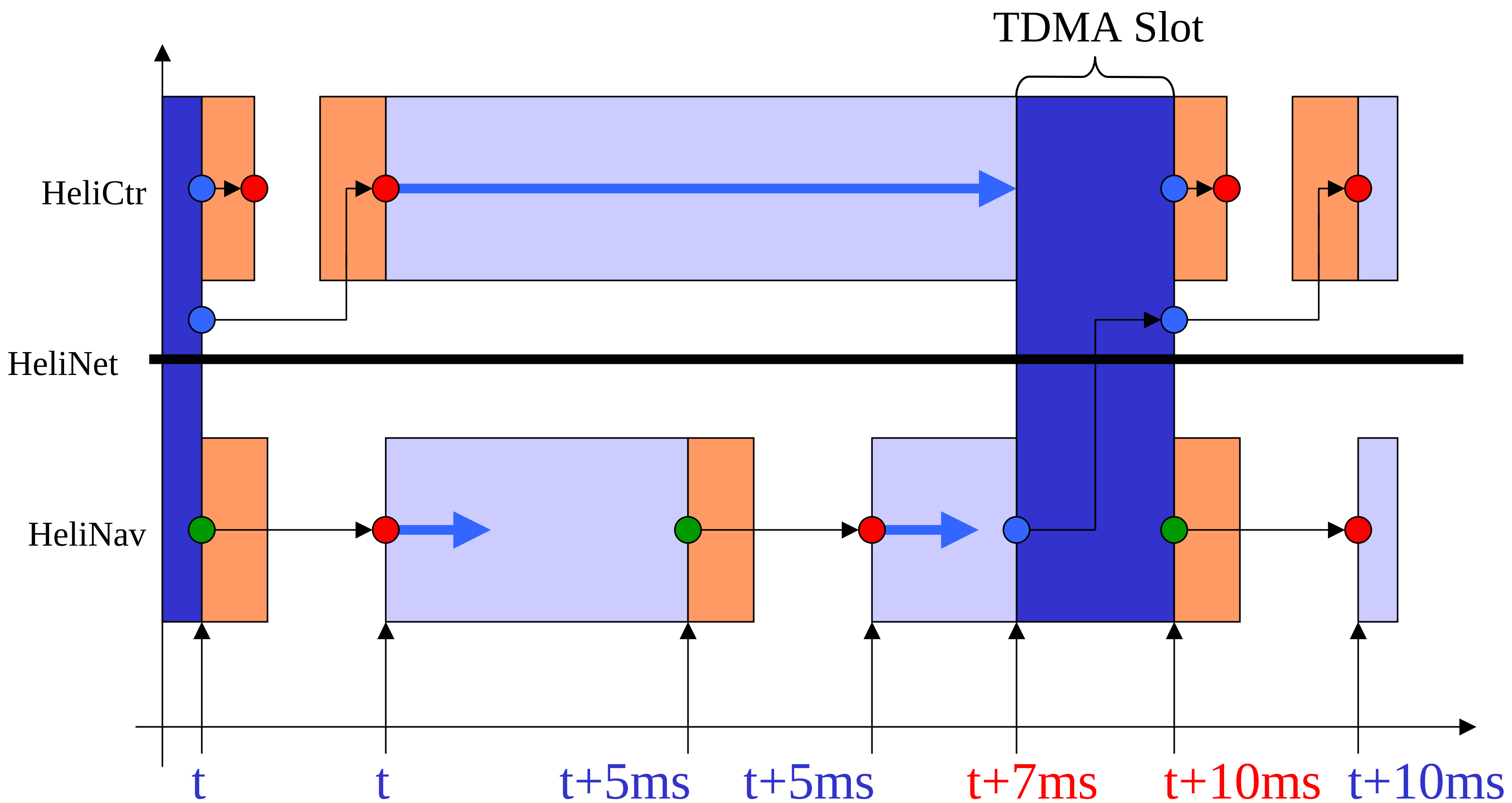


Dynamic Linking



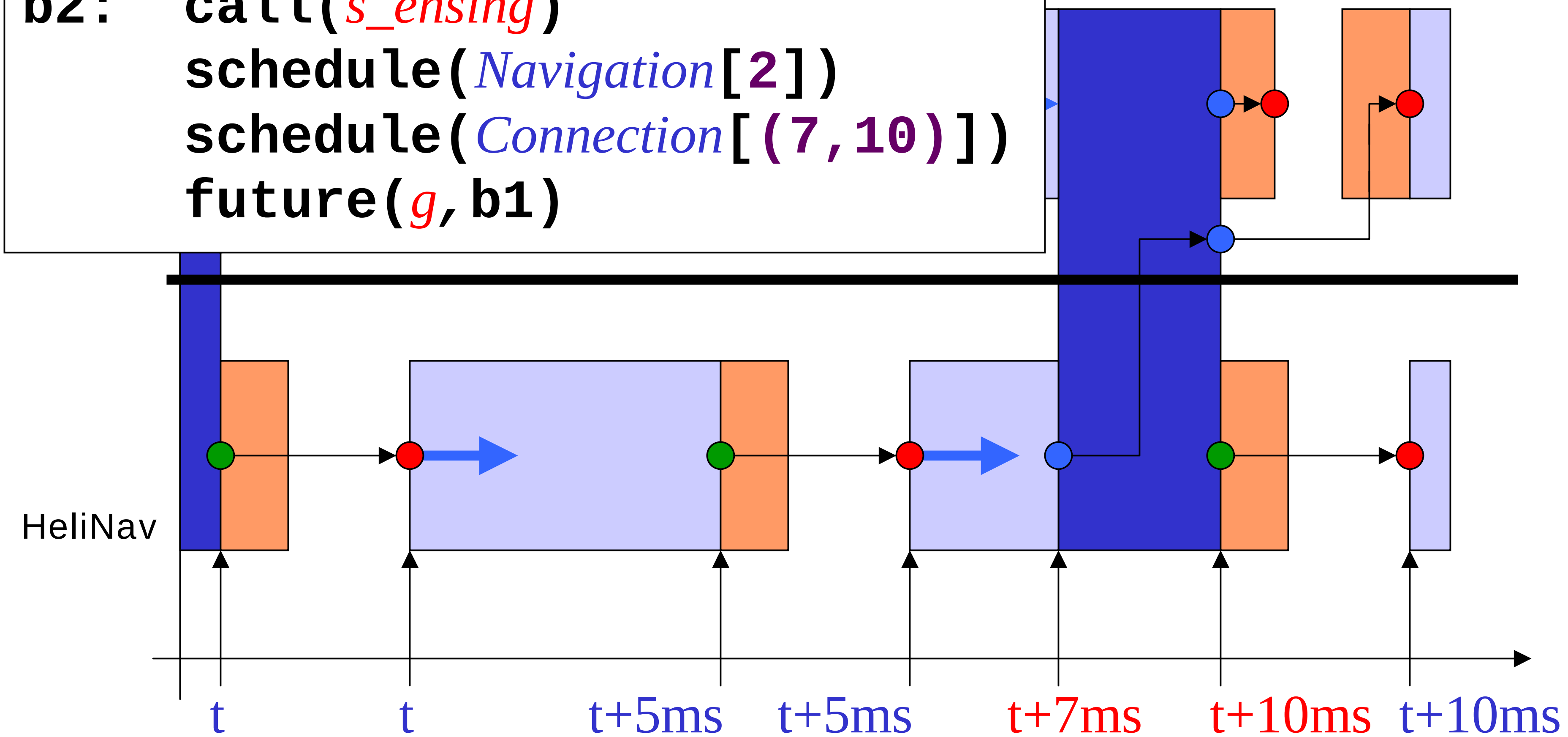
The Berkeley Helicopter

Platform Timeline: Time-triggered Communication



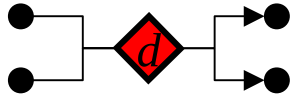
Code Generation for HeliNav

```
b2:  call(s_ensing)
     schedule(Navigation[2])
     schedule(Connection[(7,10)])
     future(g,b1)
```



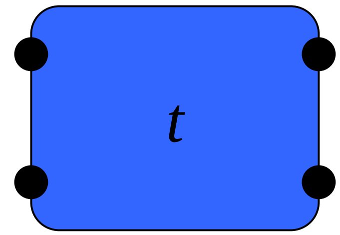
Instructions

Synchronous Driver:



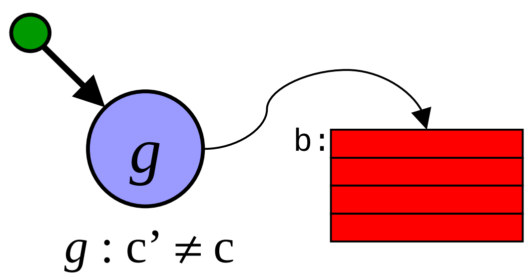
call(*d*)

Scheduled Task:



schedule(*t*)

Triggering:



future(*g*,b)