Embedded Software Engineering

3 Unit Course, Winter 2004
CS Department, Univ. of Salzburg

Chapter 1: RTOS Concepts

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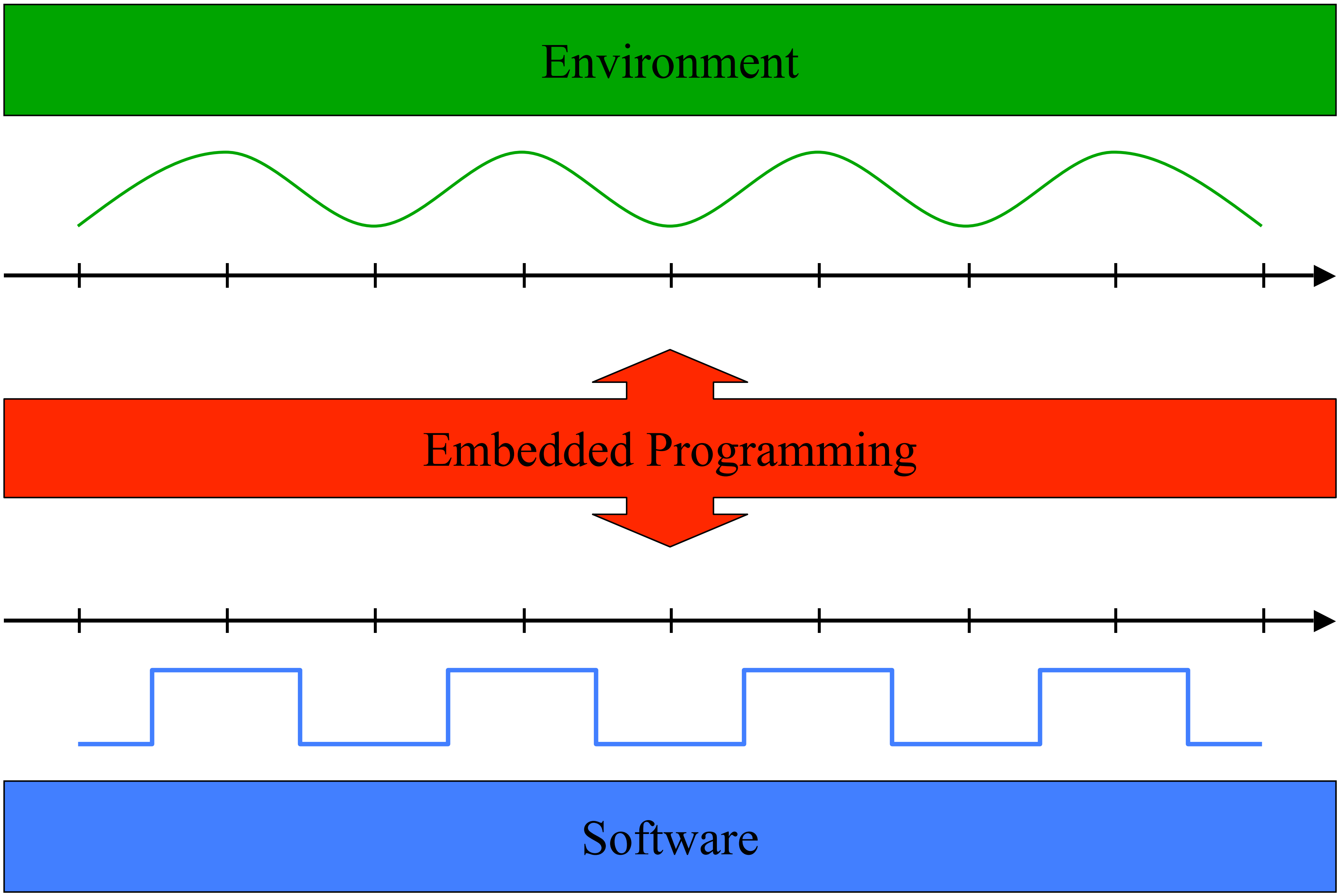
www.cs.uni-salzburg.at/~ck/teaching/ESE-Winter-2004

The Art of Embedded Programming

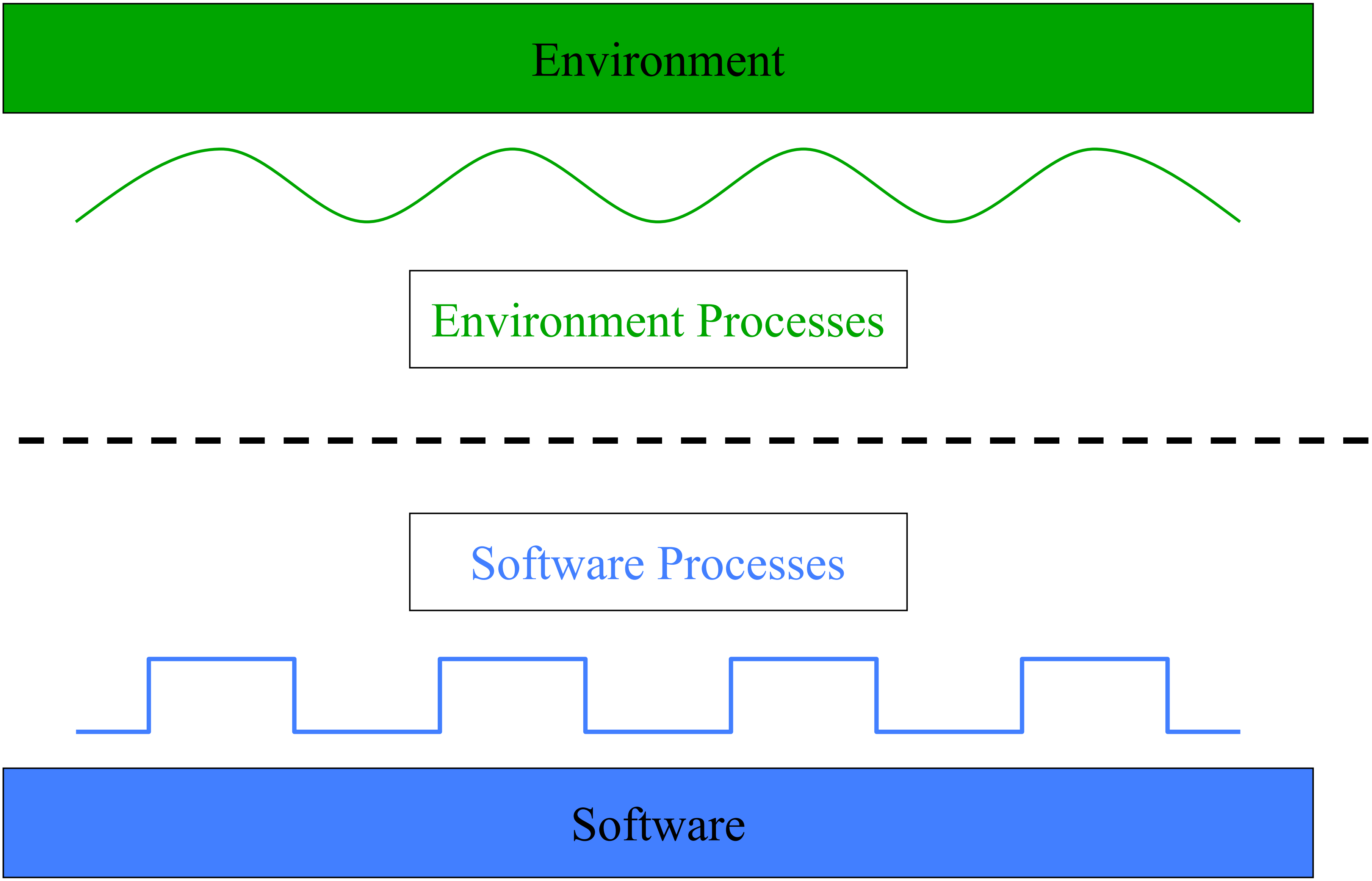


Environment

Embedded Programming

Software

What Do We Really Need From an RTOS?



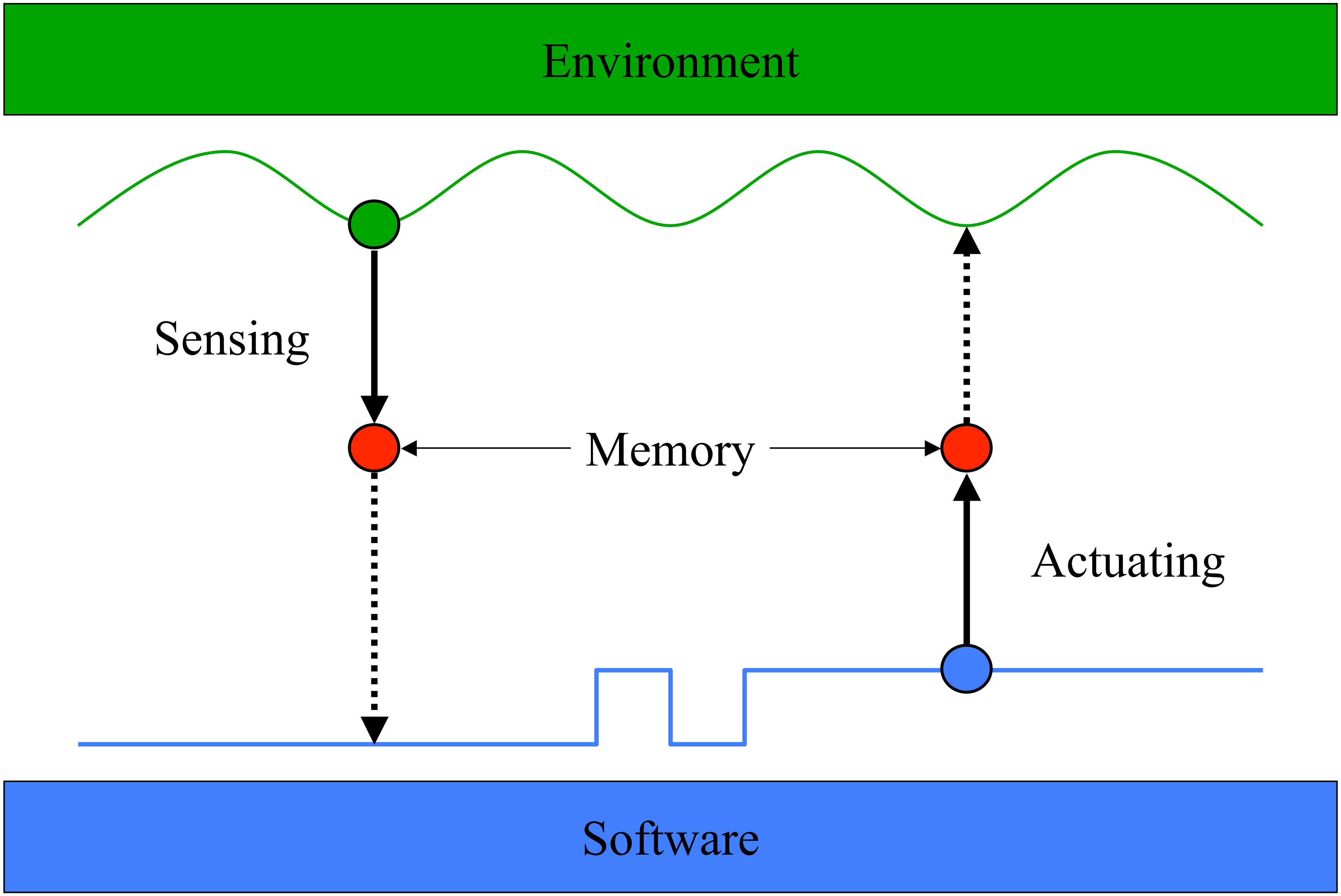
Environment

Environment Processes

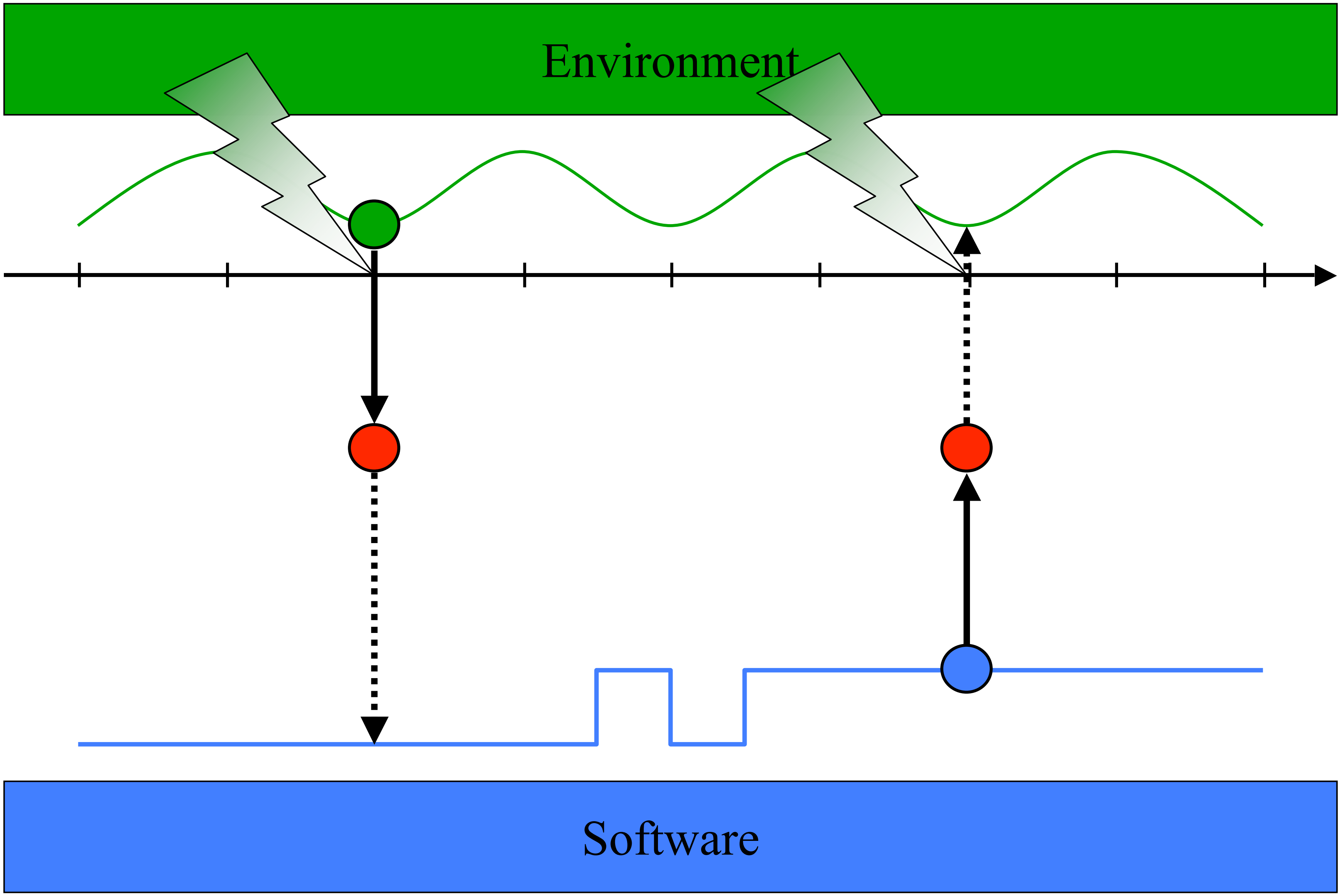
Software Processes

Software

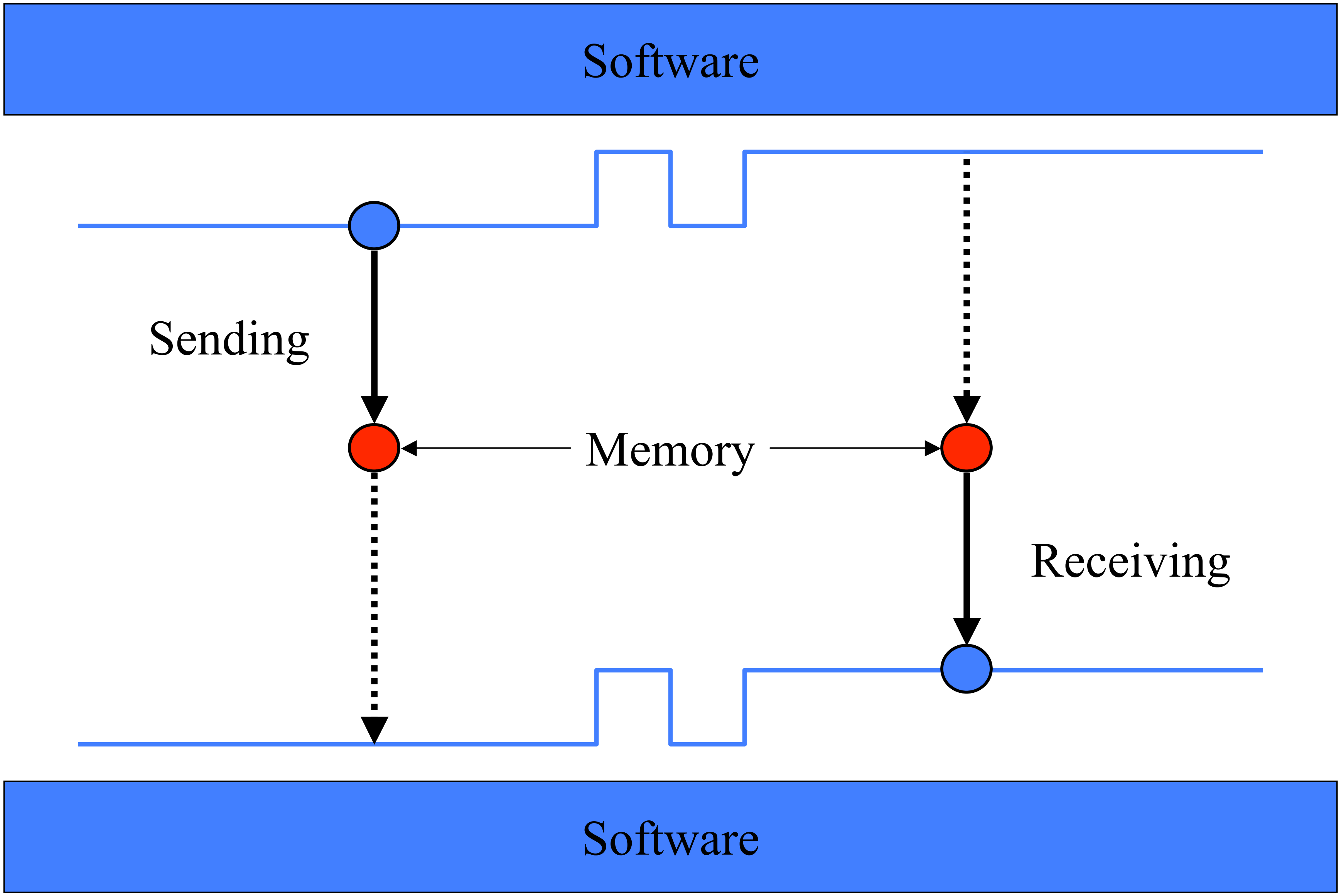
Environment Communication Services



Environment Trigger Services



Software Communication Services



Software

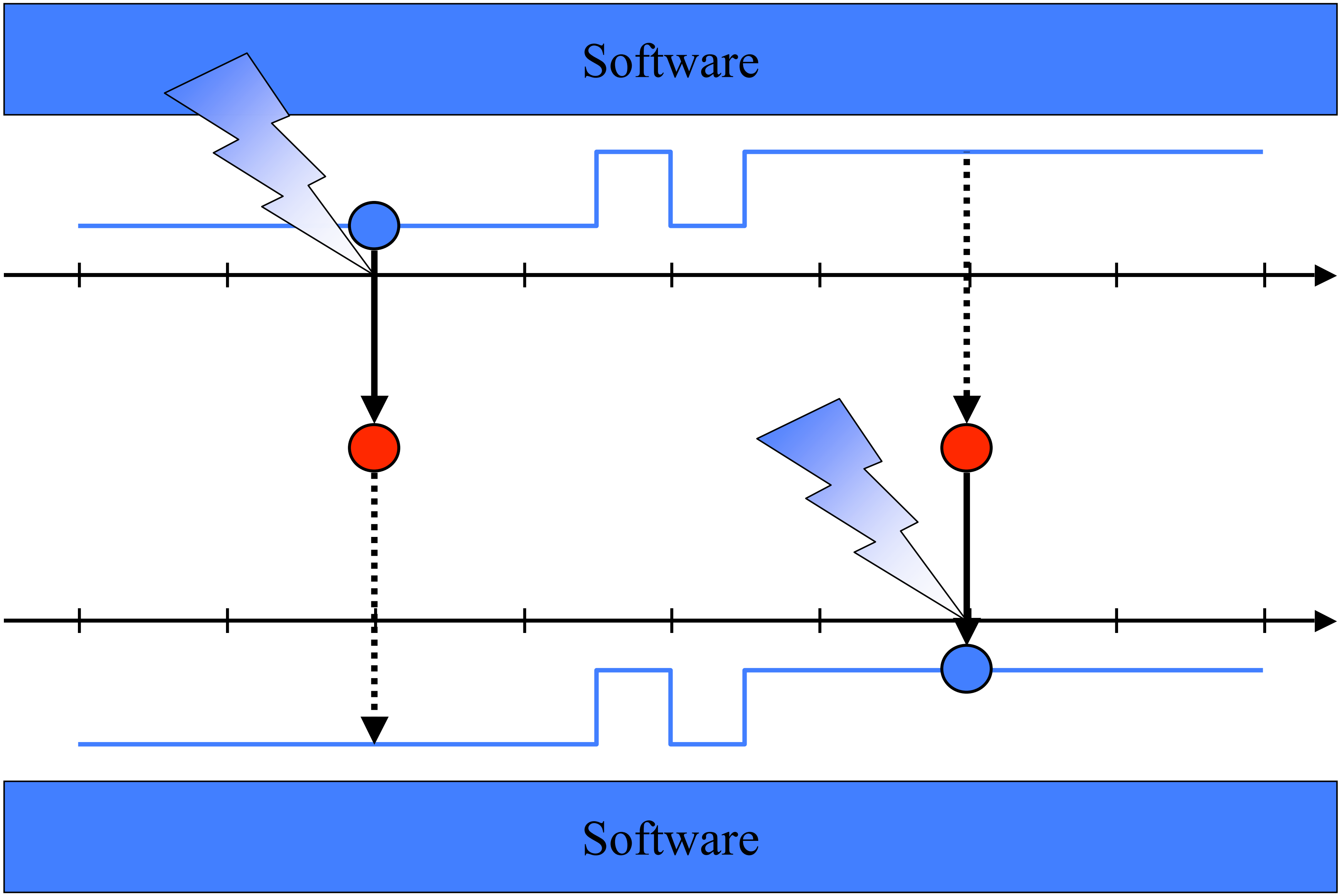
Sending

Memory

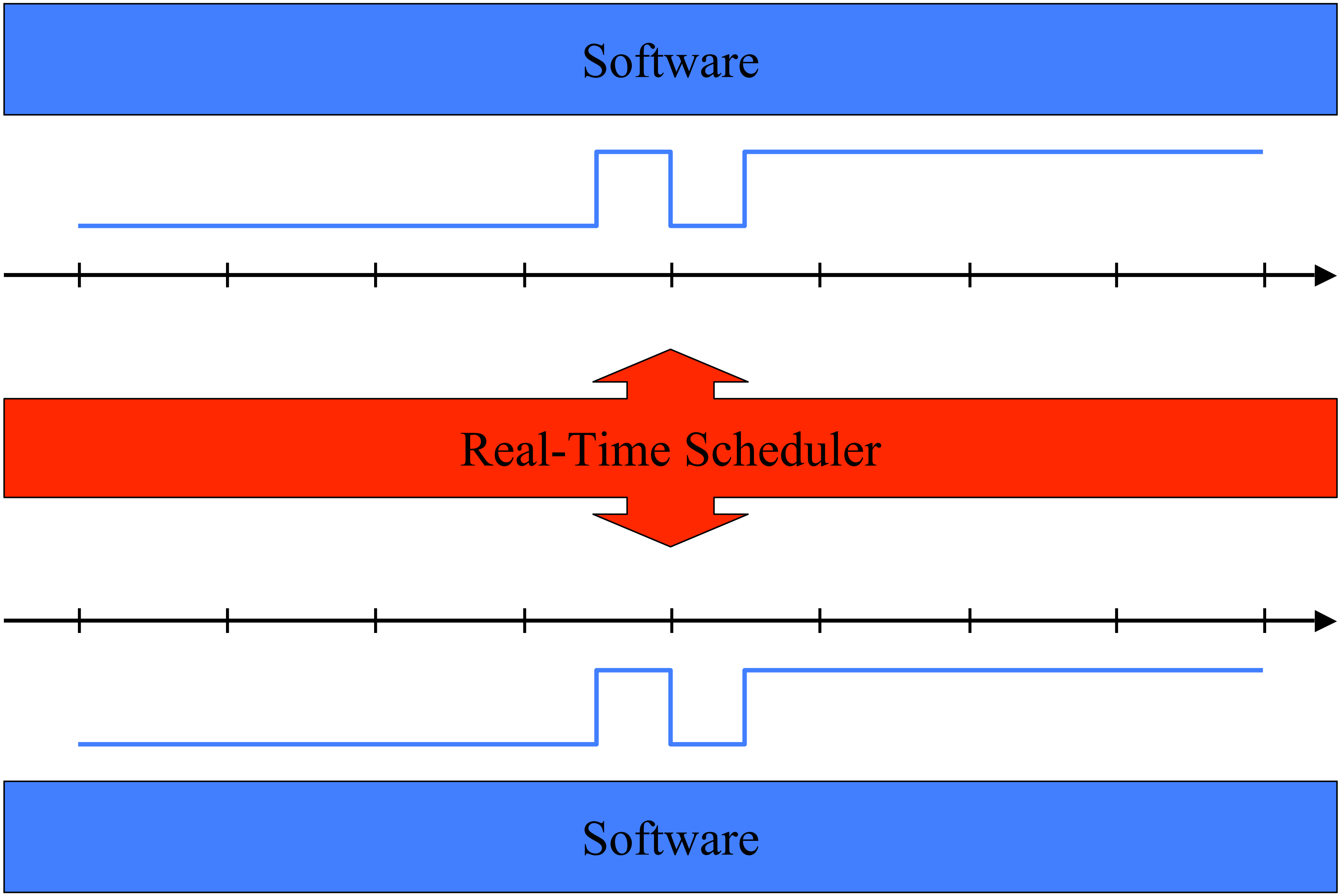
Receiving

Software

Software Trigger Services



Software Scheduling Services



Software

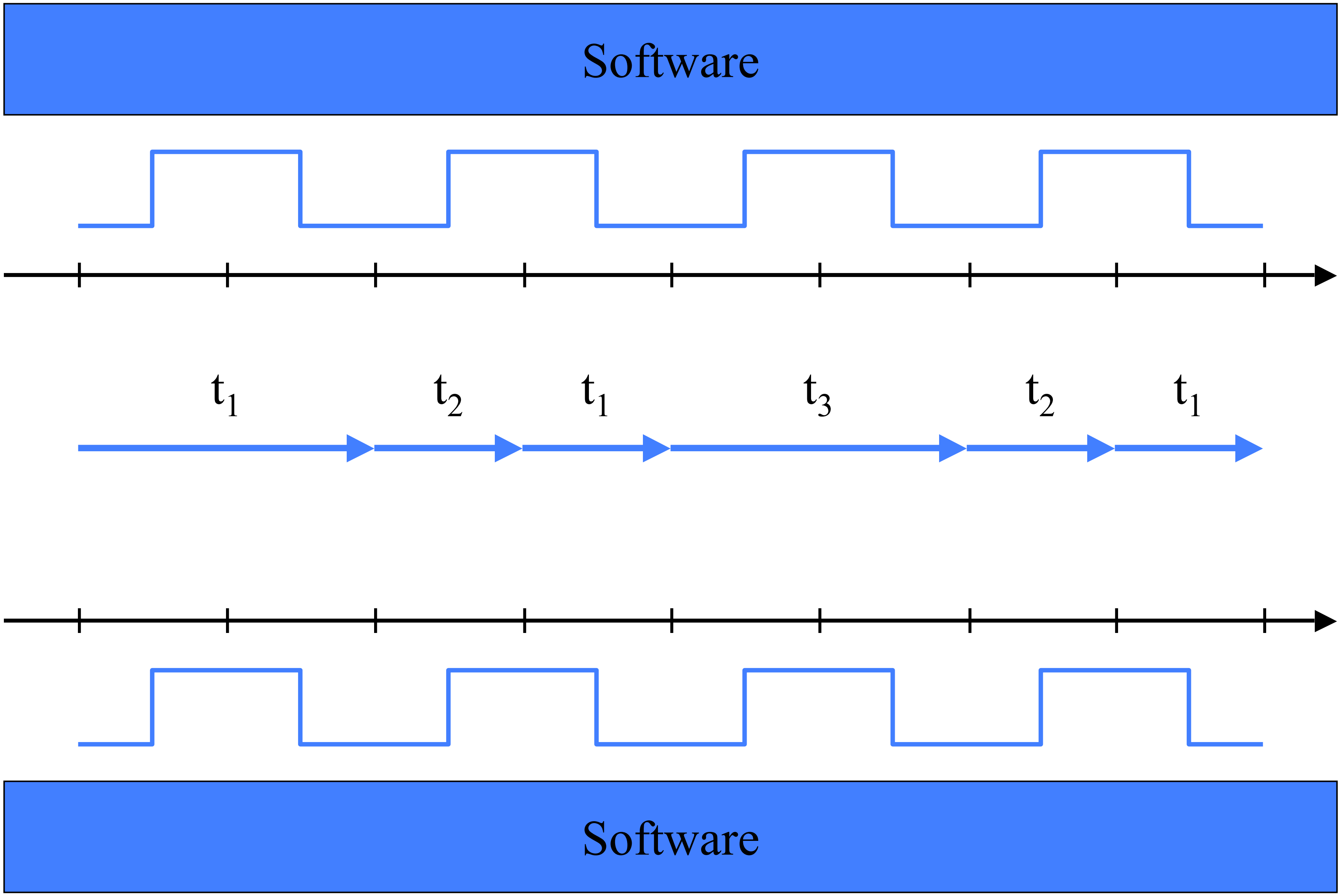
Real-Time Scheduler

Software

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

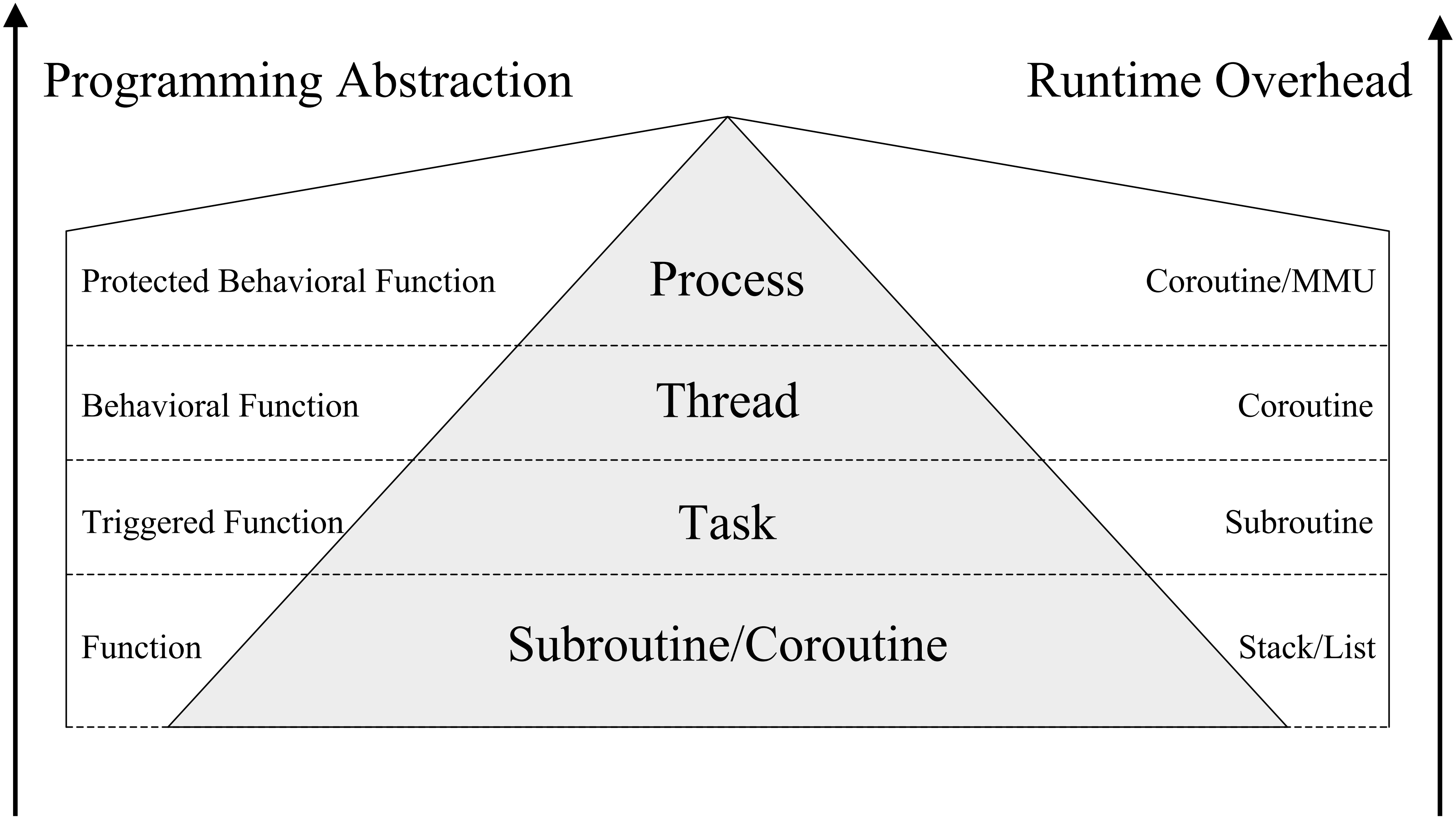


Software

t_1 t_2 t_1 t_3 t_2 t_1

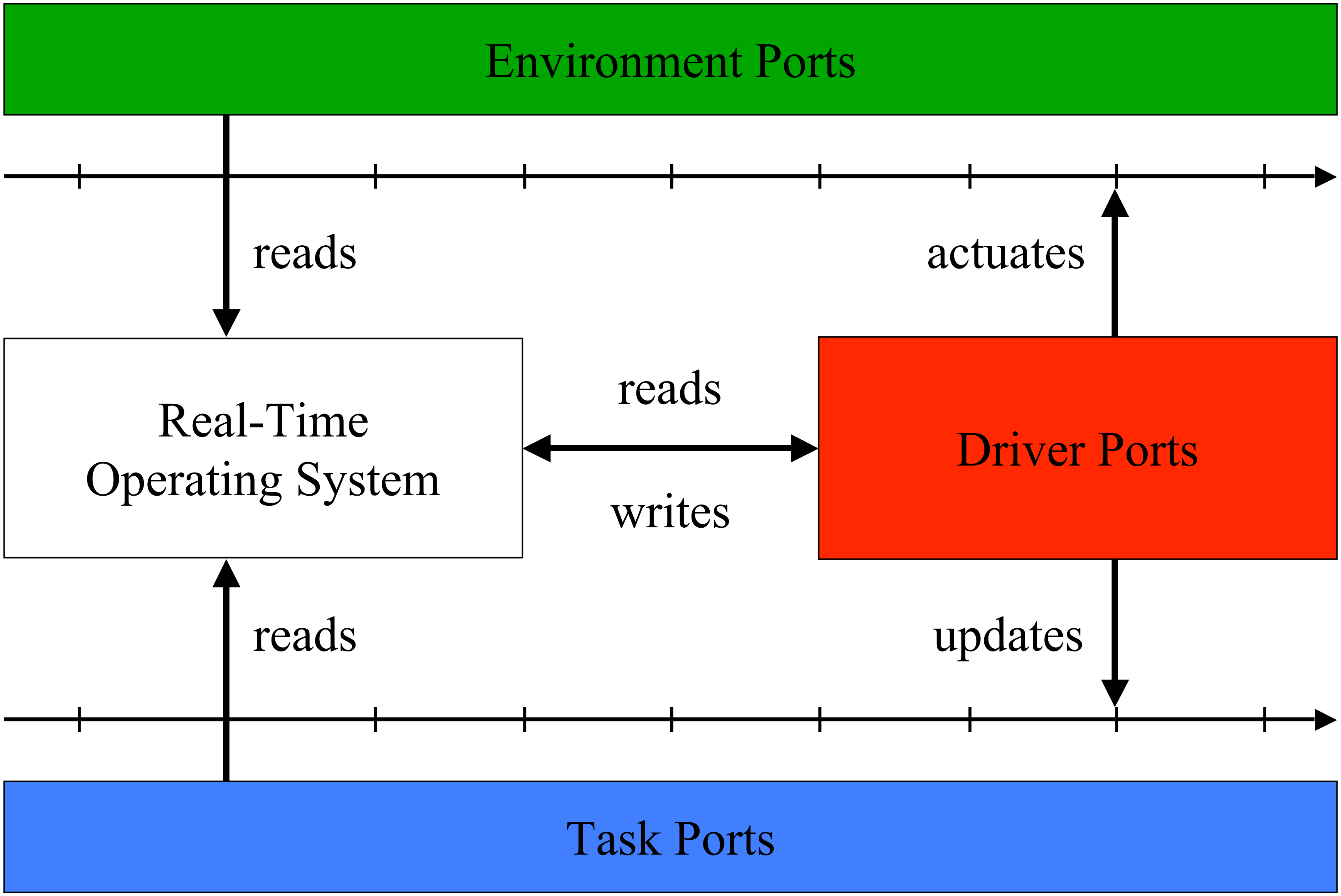
Software

Abstractions for Multiprogramming



Programming Abstraction		Runtime Overhead
Protected Behavioral Function	Process	Coroutine/MMU
Behavioral Function	Thread	Coroutine
Triggered Function	Task	Subroutine
Function	Subroutine/Coroutine	Stack/List

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)

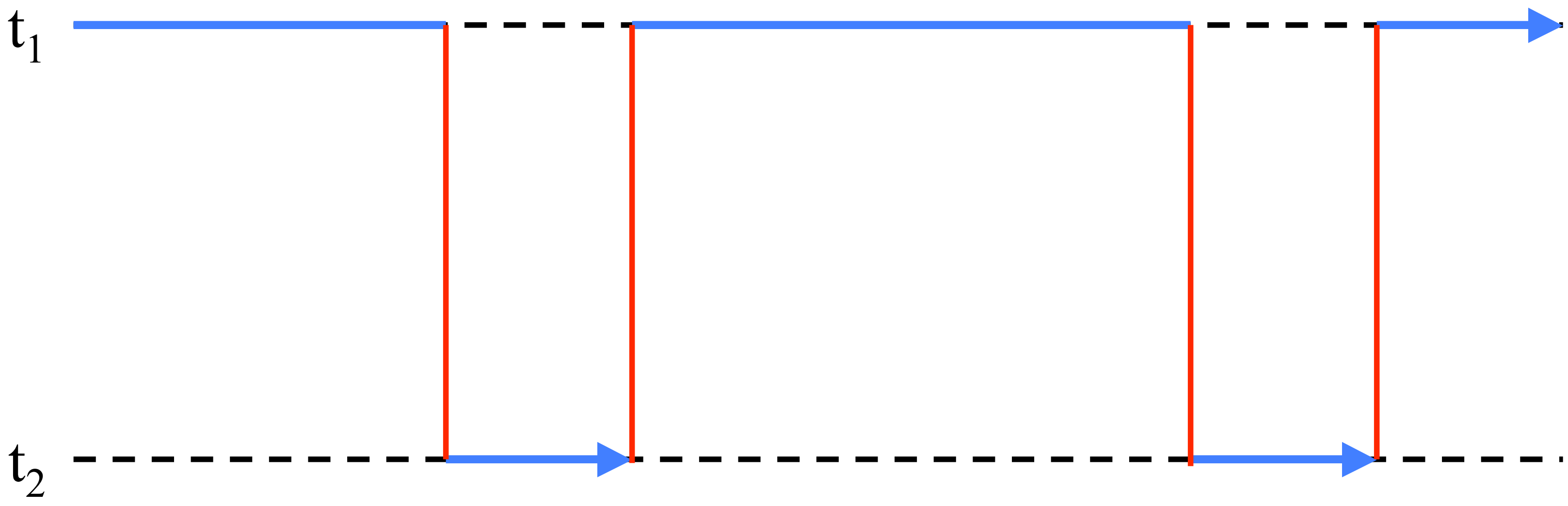
- API (used by the RTOS):
  - `initialize` {task: state ports}
  - `release` {task}
  - `dispatch` {task: function}

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

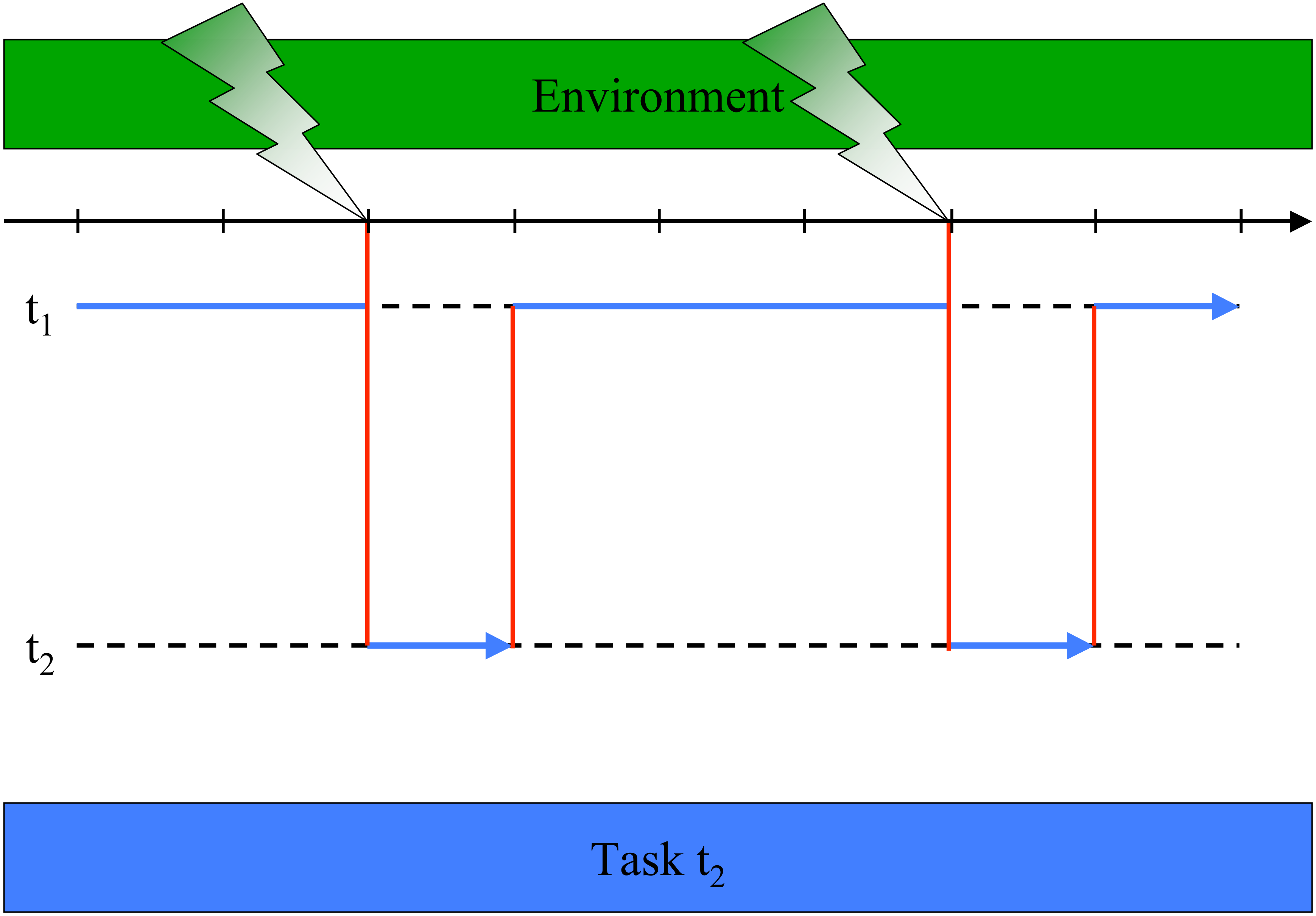
Task t_2 Preempts Task t_1

Task t_1



Task t_2

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 task ports

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

Definition: Trigger

- A trigger is a *predicate* on environment, task, 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

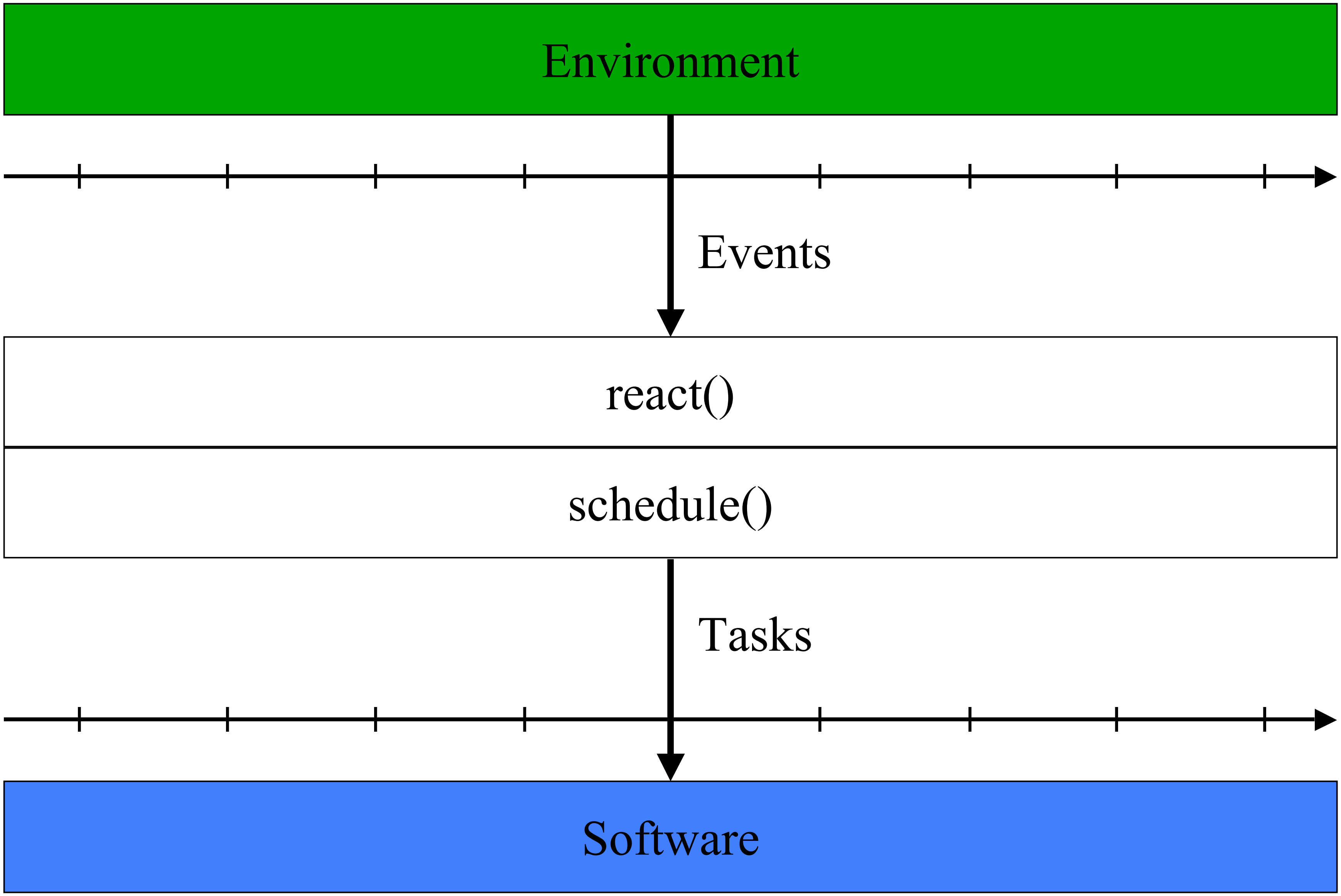
- API (used by the RTOS):
  - `activate` {trigger}
  - `cancel` {trigger}
  - `evaluate` {trigger: predicate}

My First RTOS

```
react() {
 ∀ tasks  t:  initialize(t);
 ∀ triggers g:  activate(g);
 while  (true)  {
   if ∃ trigger g:  evaluate(g)  ==  true  then
     released-tasks := ∀ to-be-released-tasks t:  release(t);
     schedule();
 }
}
```

```
schedule() {
   ∀ released-tasks t:  dispatch(t);
   released-tasks :=  {};
}
```

RTOS Model: Reaction vs. Scheduling



Environment

Events

react()

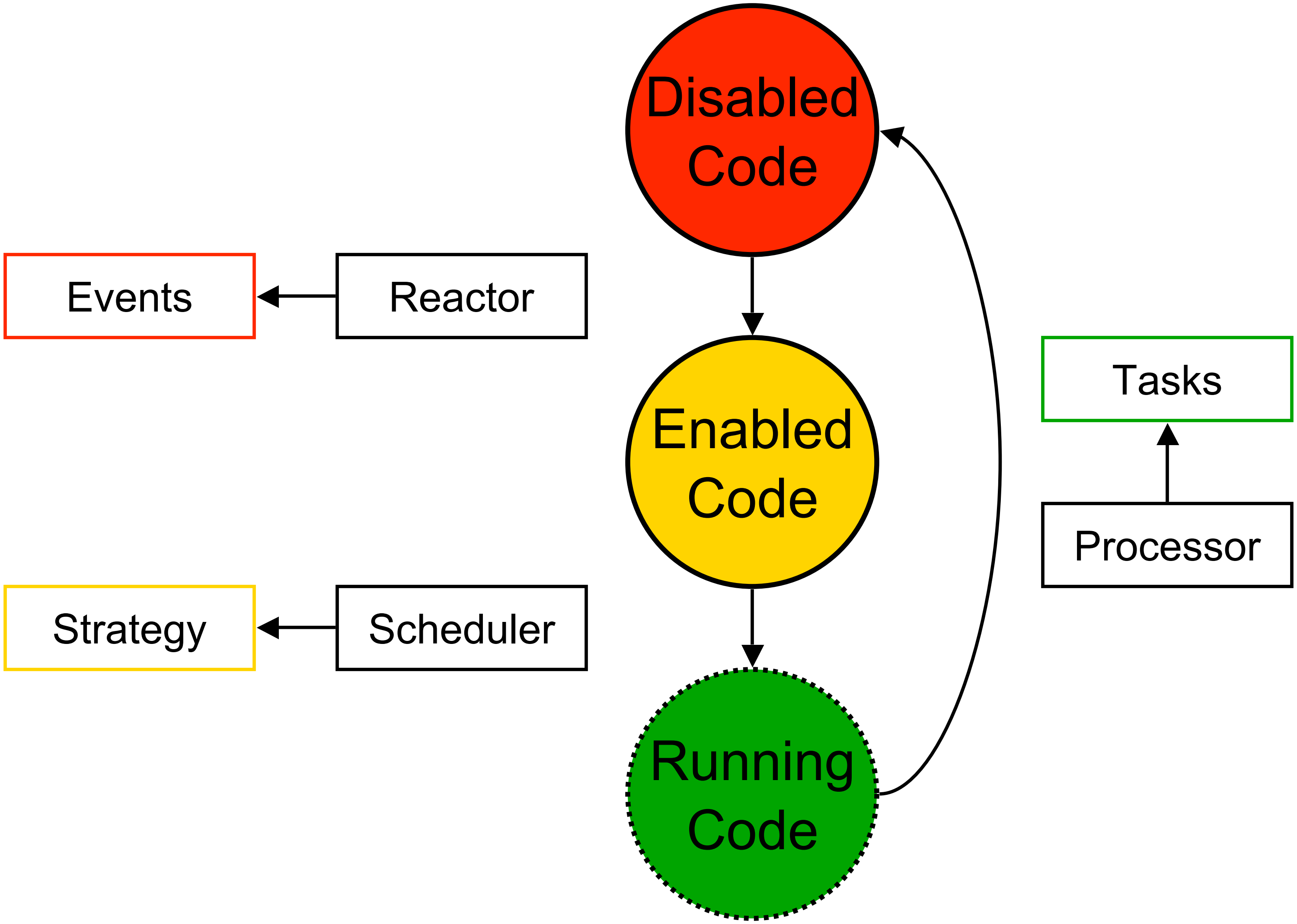
schedule()

Tasks

Software

Reactor vs. Scheduler vs. Processor

(Kirsch in the Proceedings of EMSOFT 2002)



RTOS with Preemption

```
react() {
 ∀ tasks t: initialize(t);
 ∀ triggers g: activate(g);
 while (true) {
  if ∃ trigger g: evaluate(g) == true then
   released-tasks := ∀ to-be-released-tasks t: release(t);
   schedule_concurrently();
 }
}
```

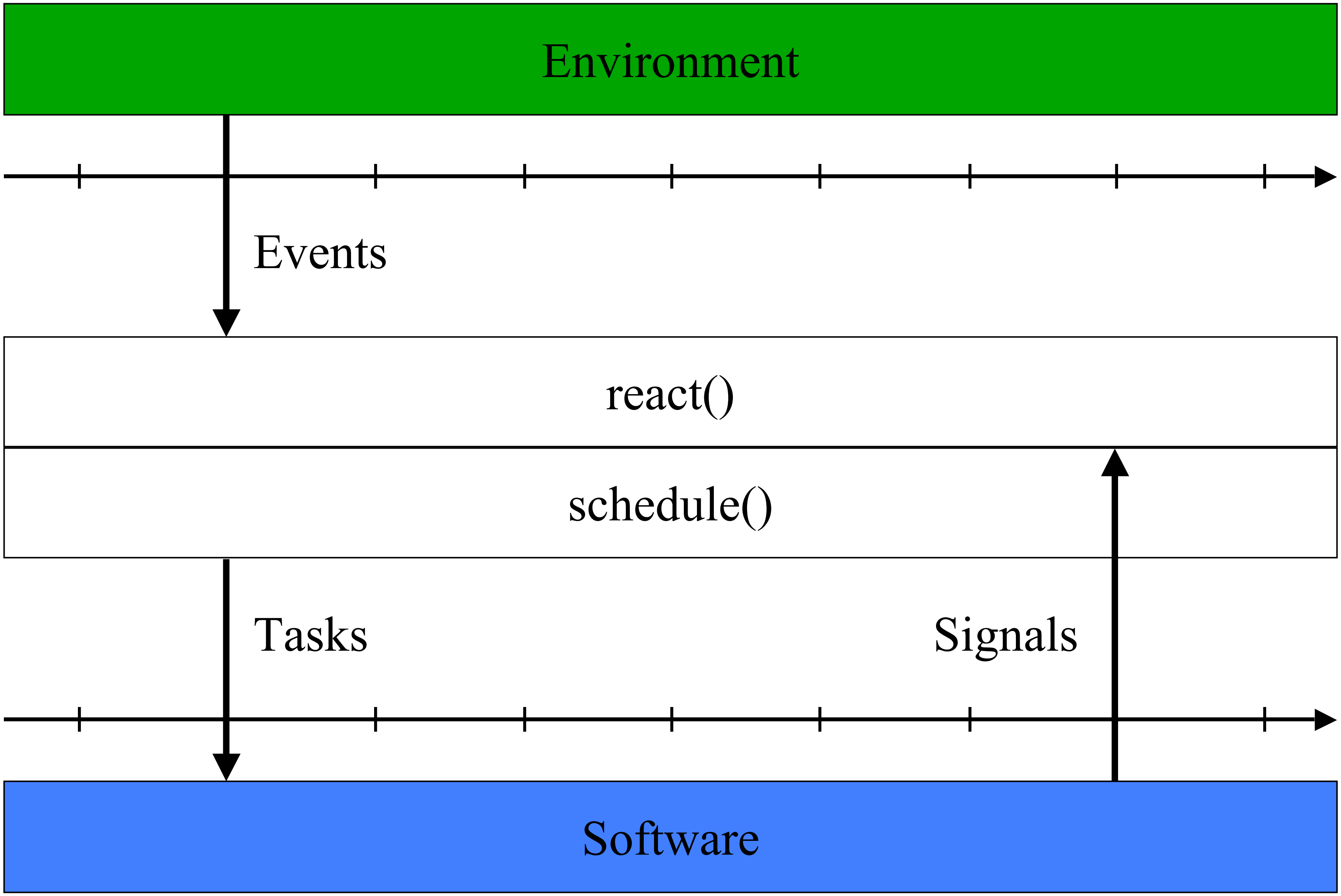
```
schedule_concurrently() {
  ∀ released-tasks t: dispatch(t);
  released-tasks := {};
}
```

Corrected RTOS with Preemption

```
react() {
 ∀ tasks t: initialize(t);
 ∀ triggers g: activate(g);
 while (true) {
  if ∃ trigger g: evaluate(g) == true then
   released-tasks := released-tasks ∪
                   ∀ to-be-released-tasks t: release(t);}}
```

```
schedule() {
 while (true) {
  t := select(released-tasks);
  dispatch(t);
  released-tasks := released-tasks \ { t }; }}
```

RTOS Model with Signals



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*

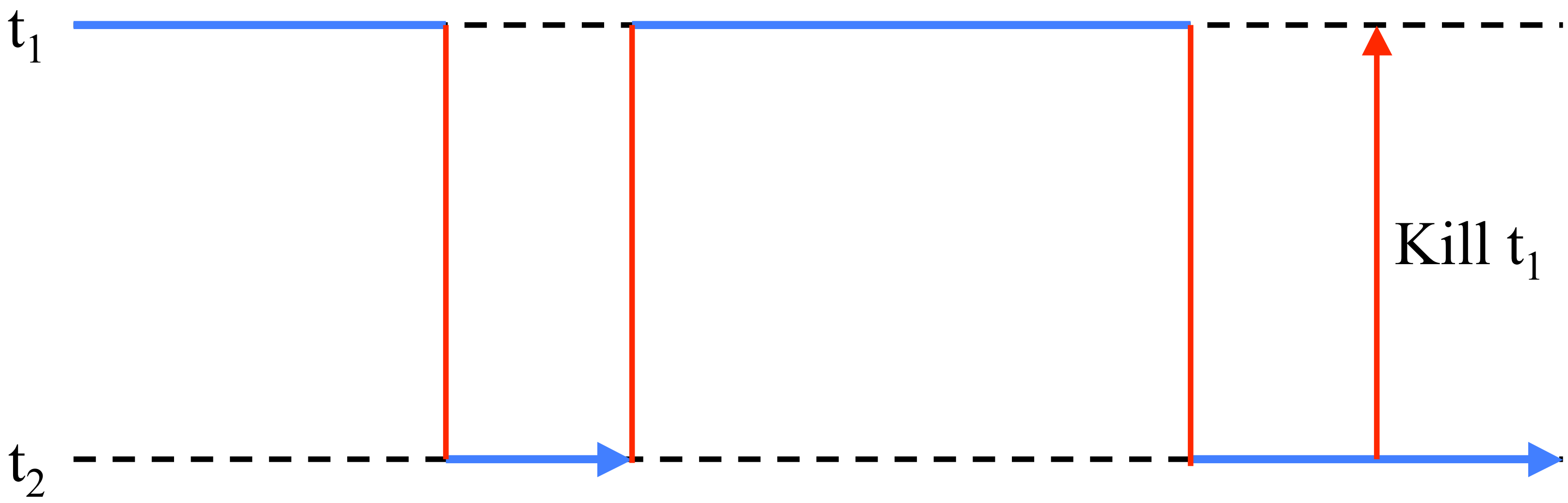
- API (used by the RTOS or threads):
  - `initialize` {thread: ports}
  - `release` {thread}
  - `dispatch` {thread: function}
  - `kill` {thread}

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

Task t_1



Task t_2

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);
                                        must be atomic
  semaphore.lock := true;
}

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

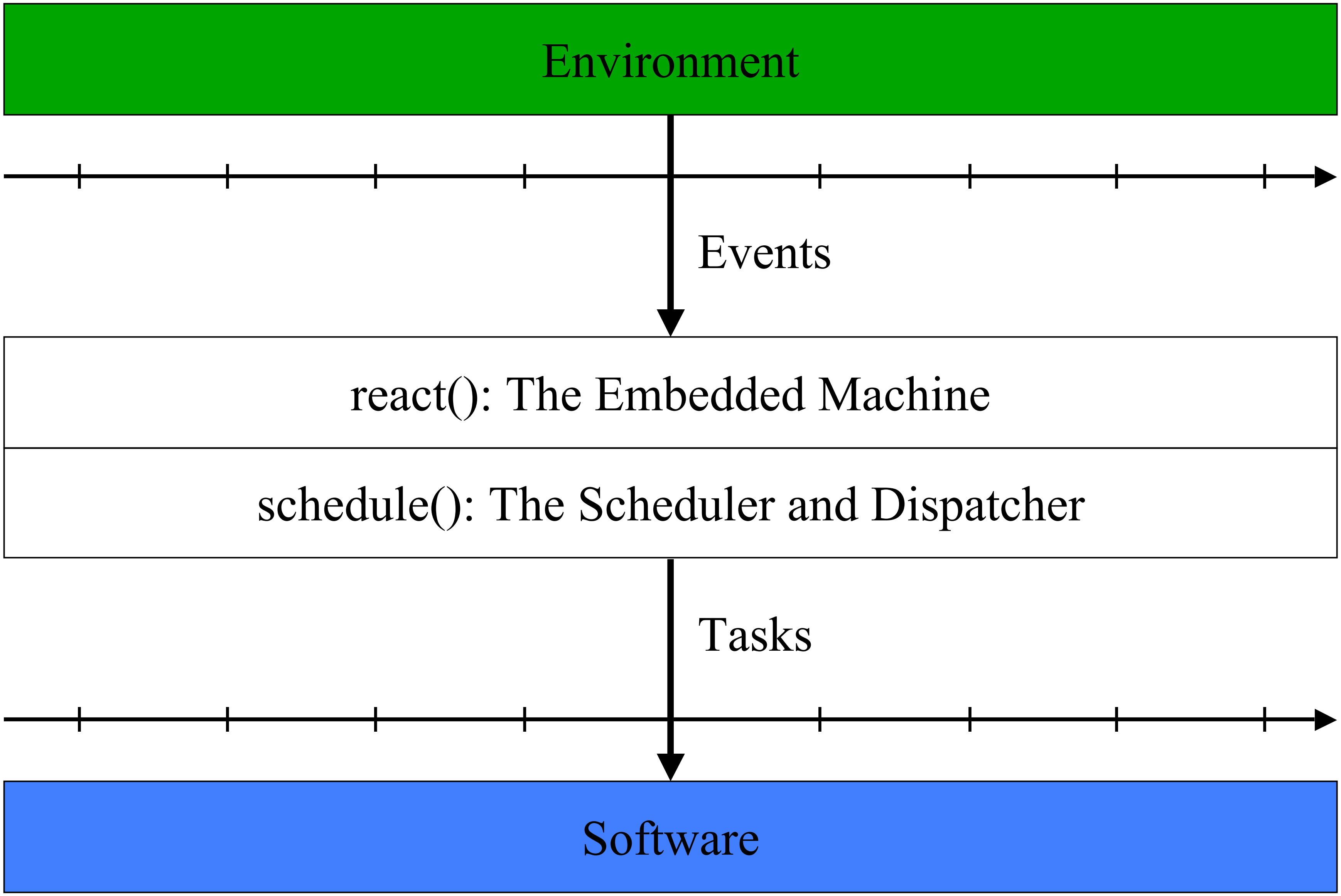
Binary Semaphore (Busy Wait)

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

each round must be atomic

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

The Embedded Machine



Environment

Events

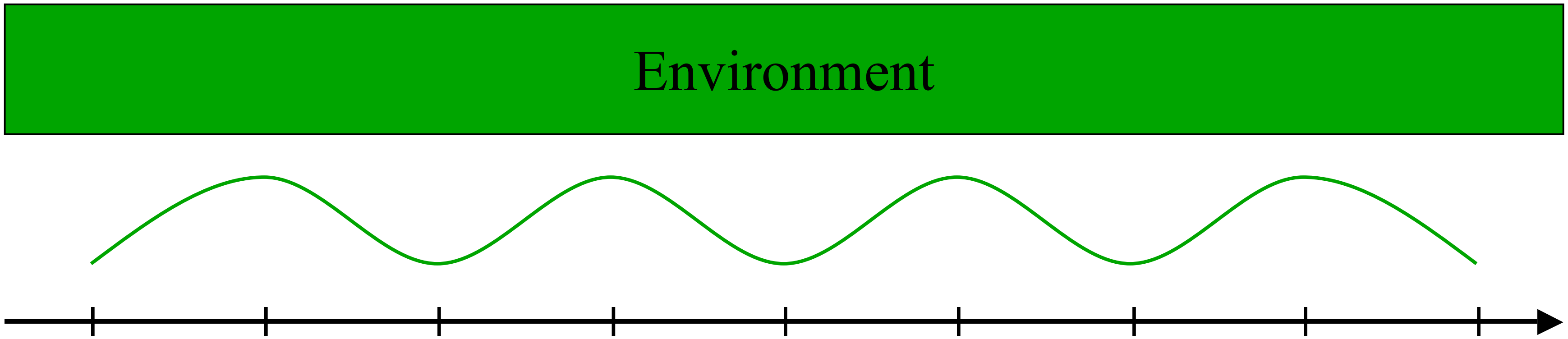
react(): The Embedded Machine

schedule(): The Scheduler and Dispatcher

Tasks

Software

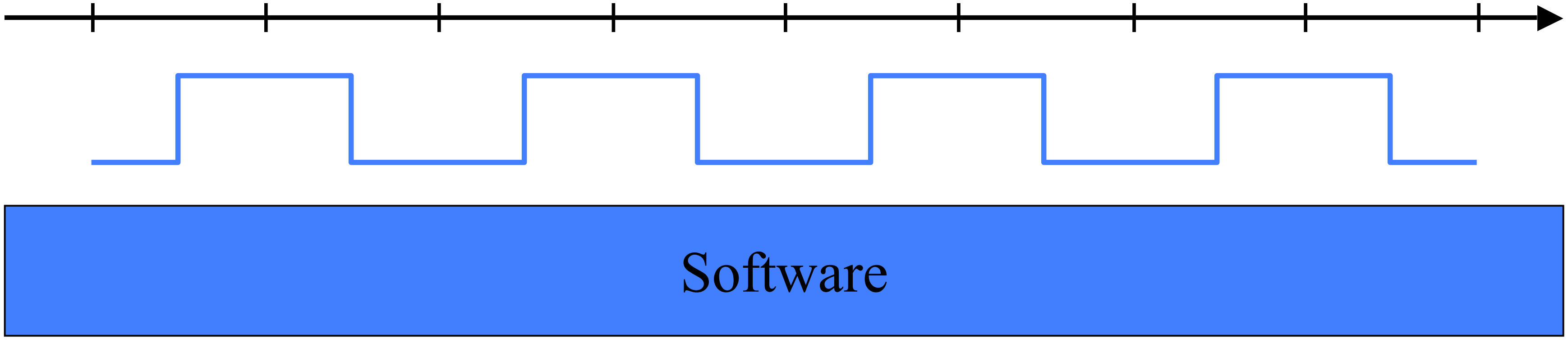
Proposal



Environment

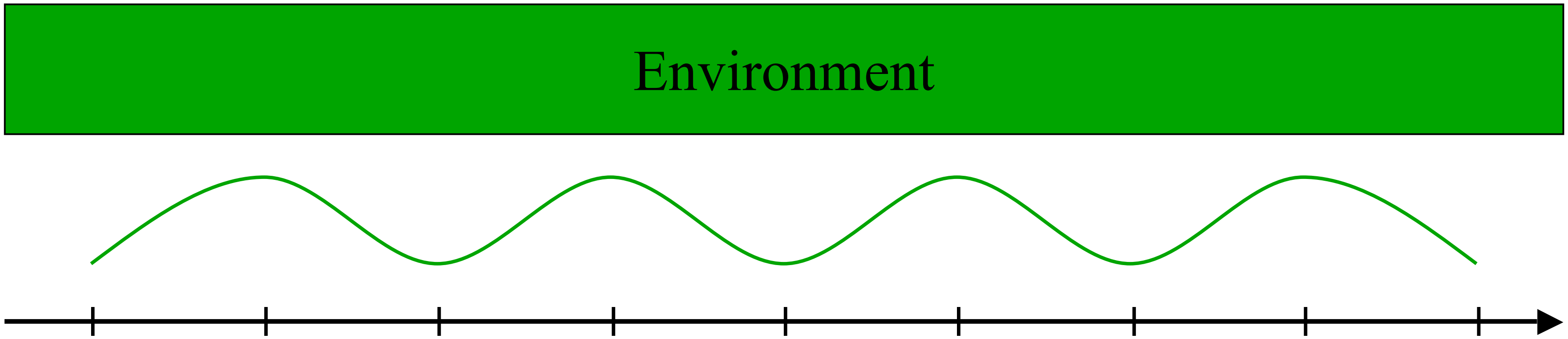
<span style="color:red">Human:</span> Programming in terms of environment time

Compiler: Implementation in terms of platform time



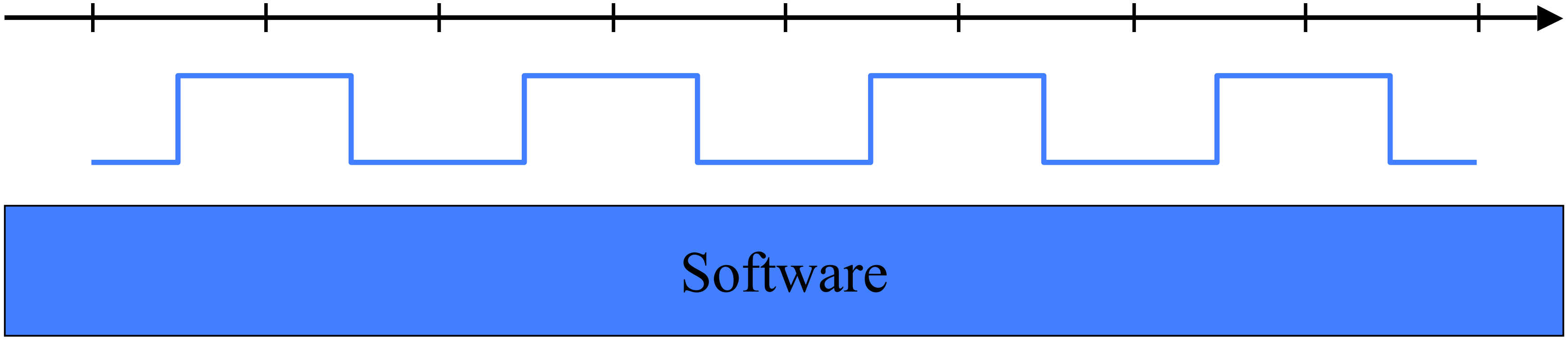
Software

Platform Time is Platform Memory

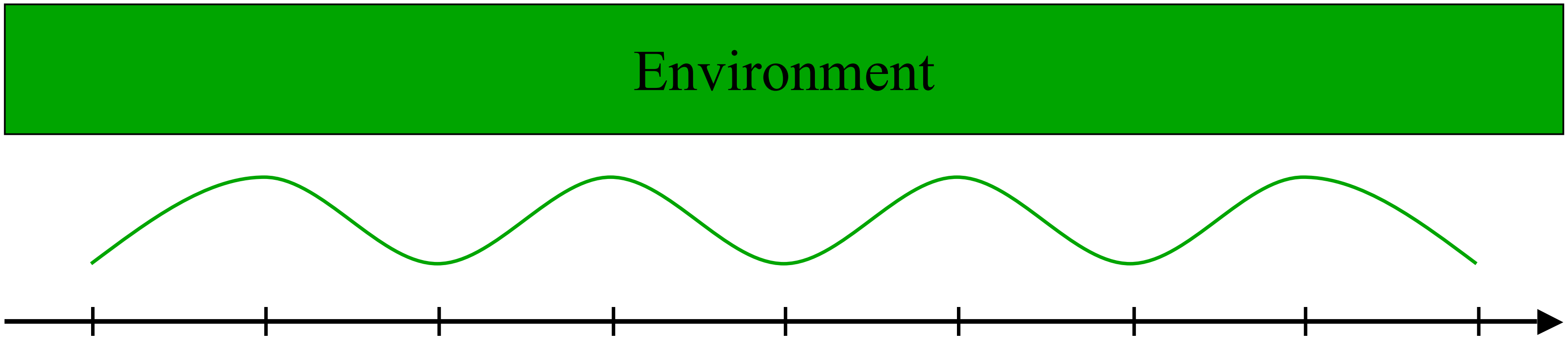


- Programming as if there is enough platform time

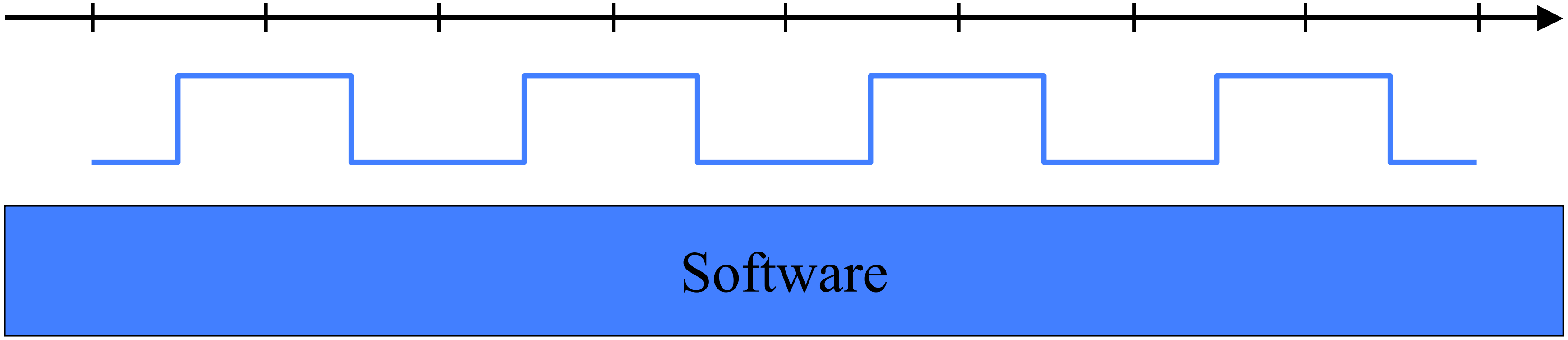
- Implementation checks whether there is enough of it



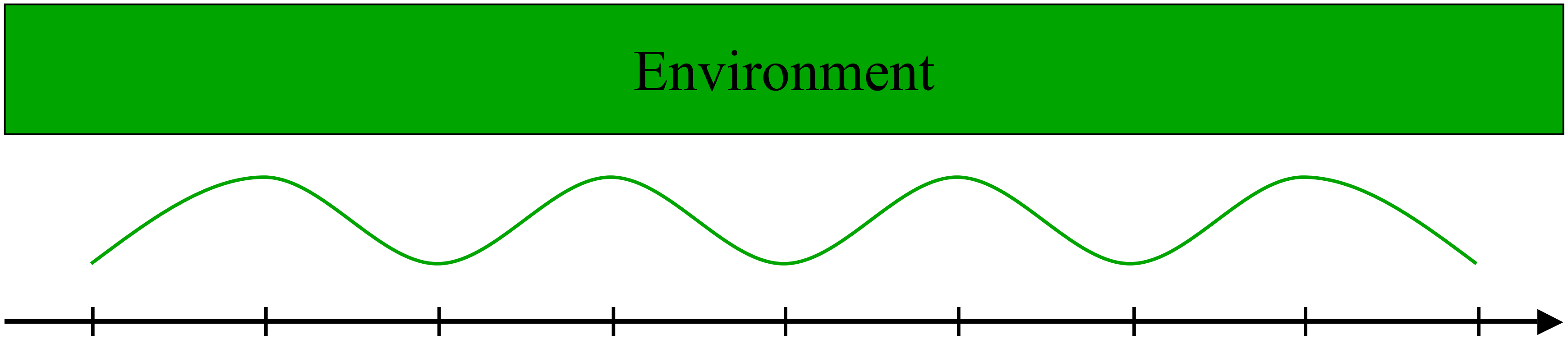
Portability



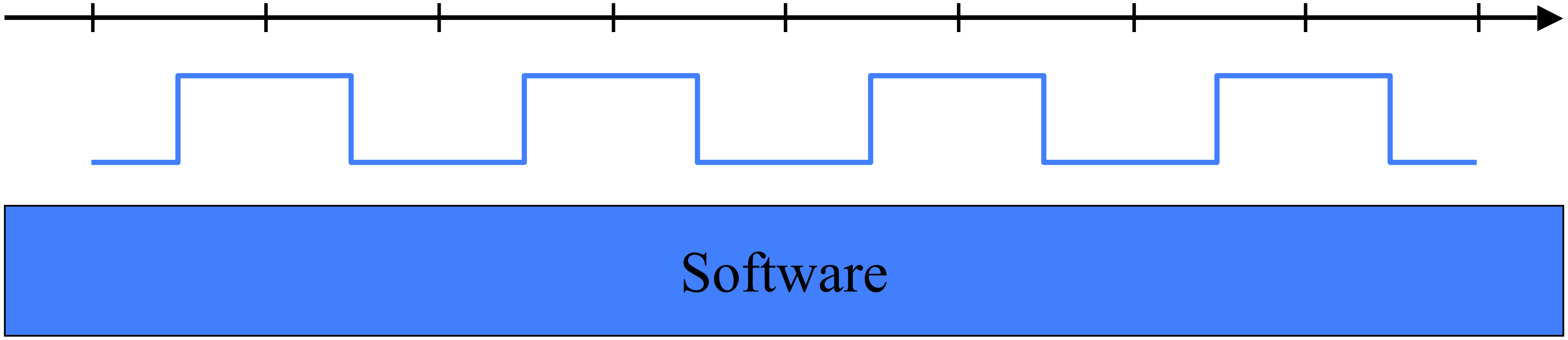
- Programming in terms of environment time yields platform-independent code



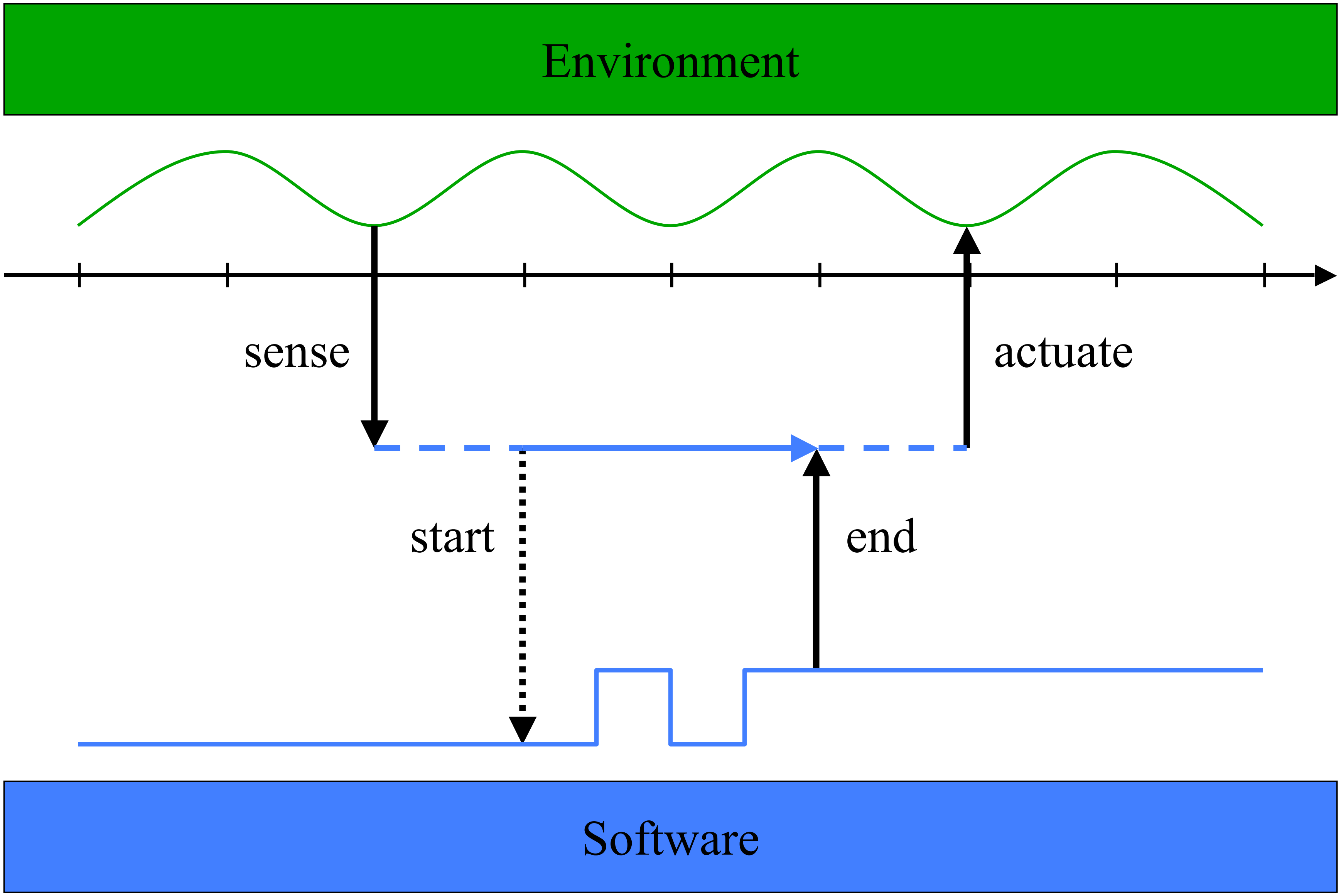
Predictability



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



The Task Model



Environment

sense

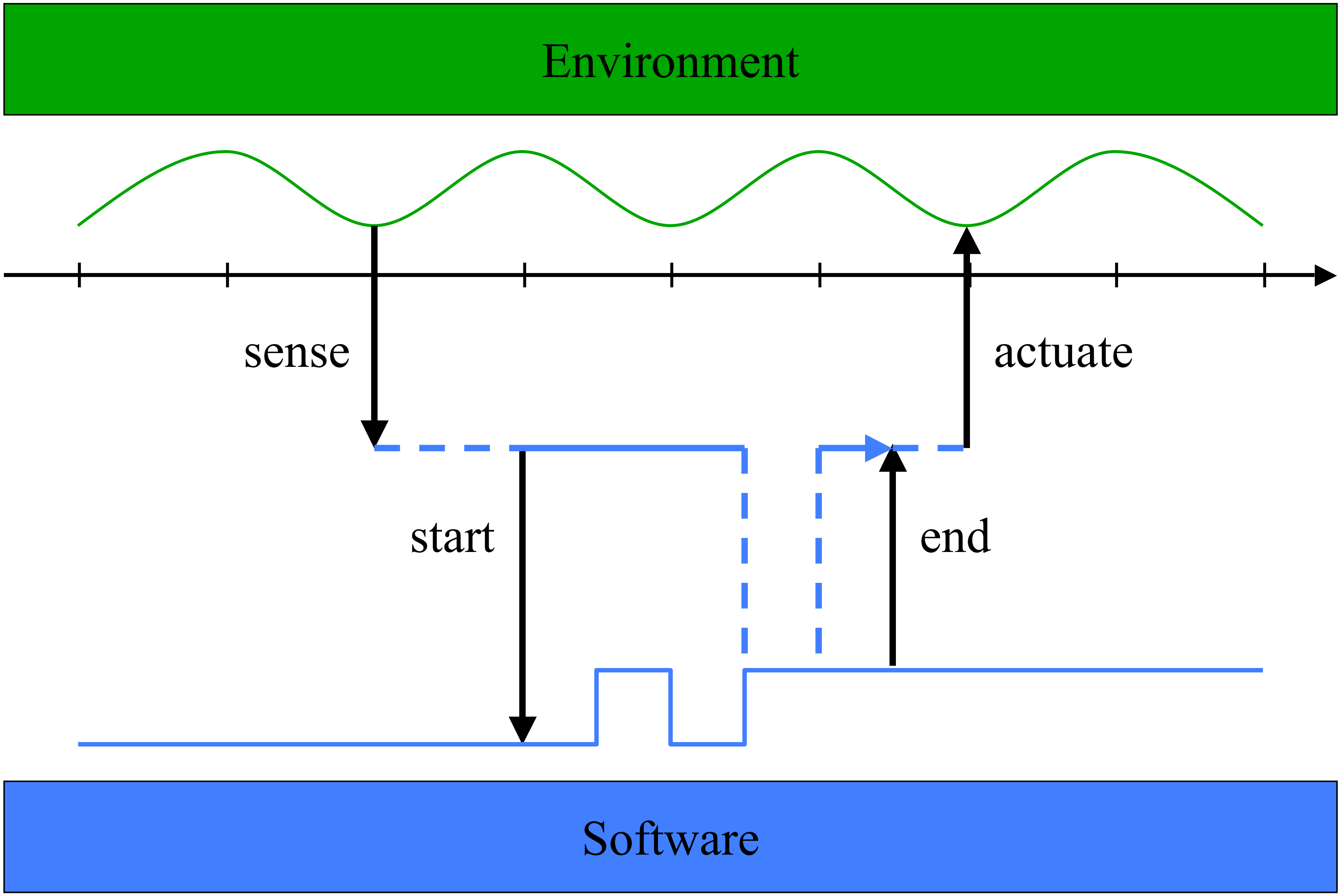
actuate

start

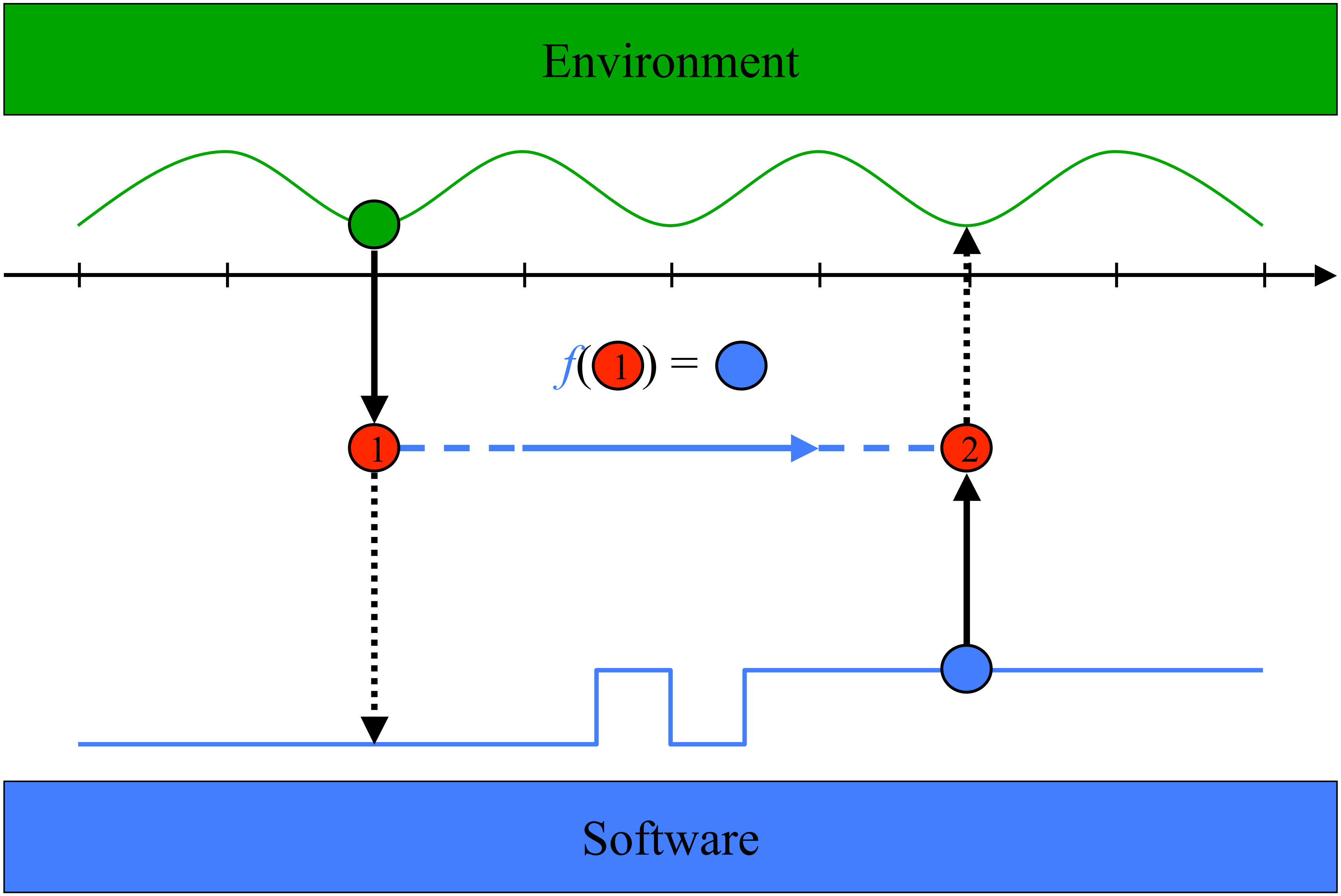
end

Software

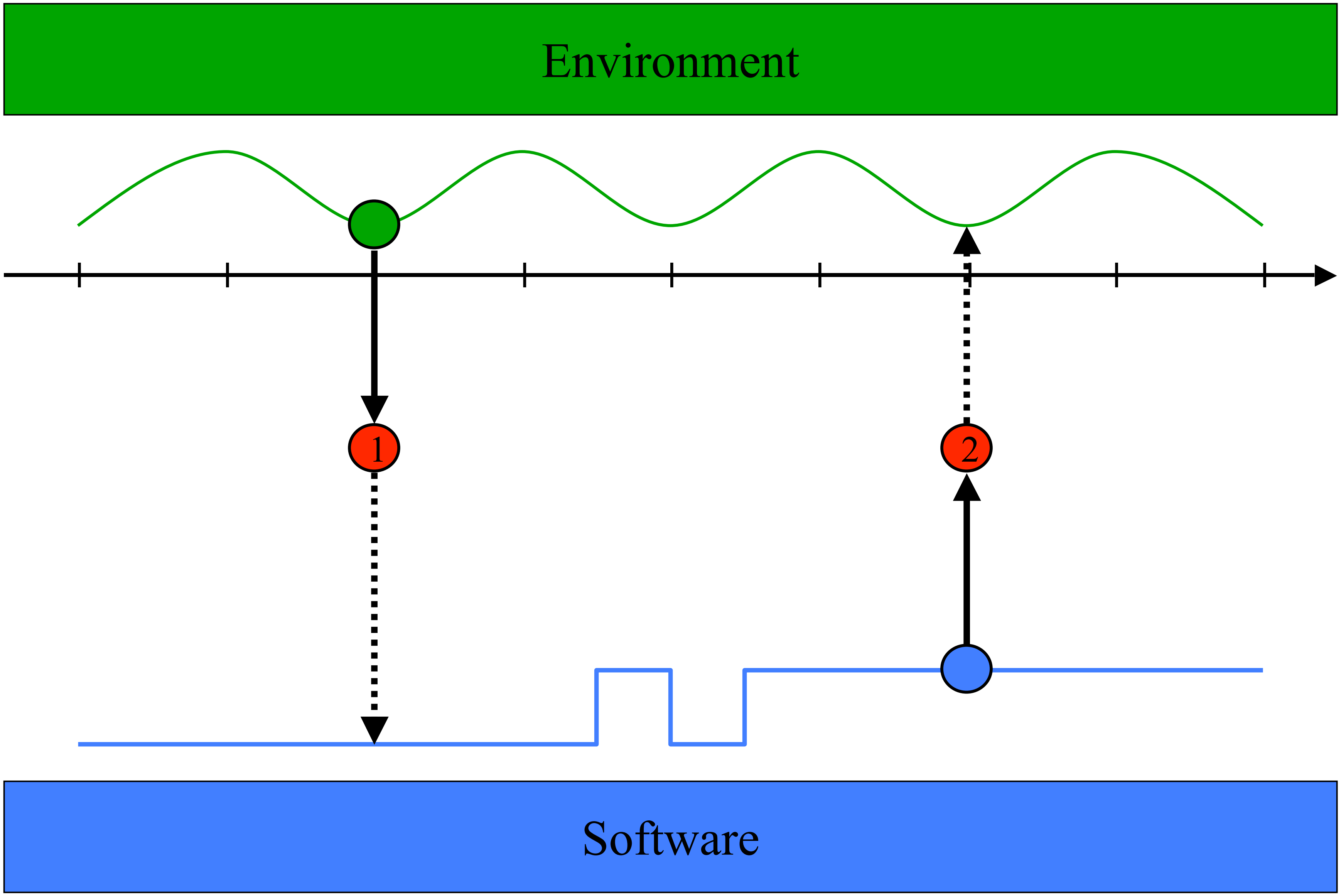
Preemptable…



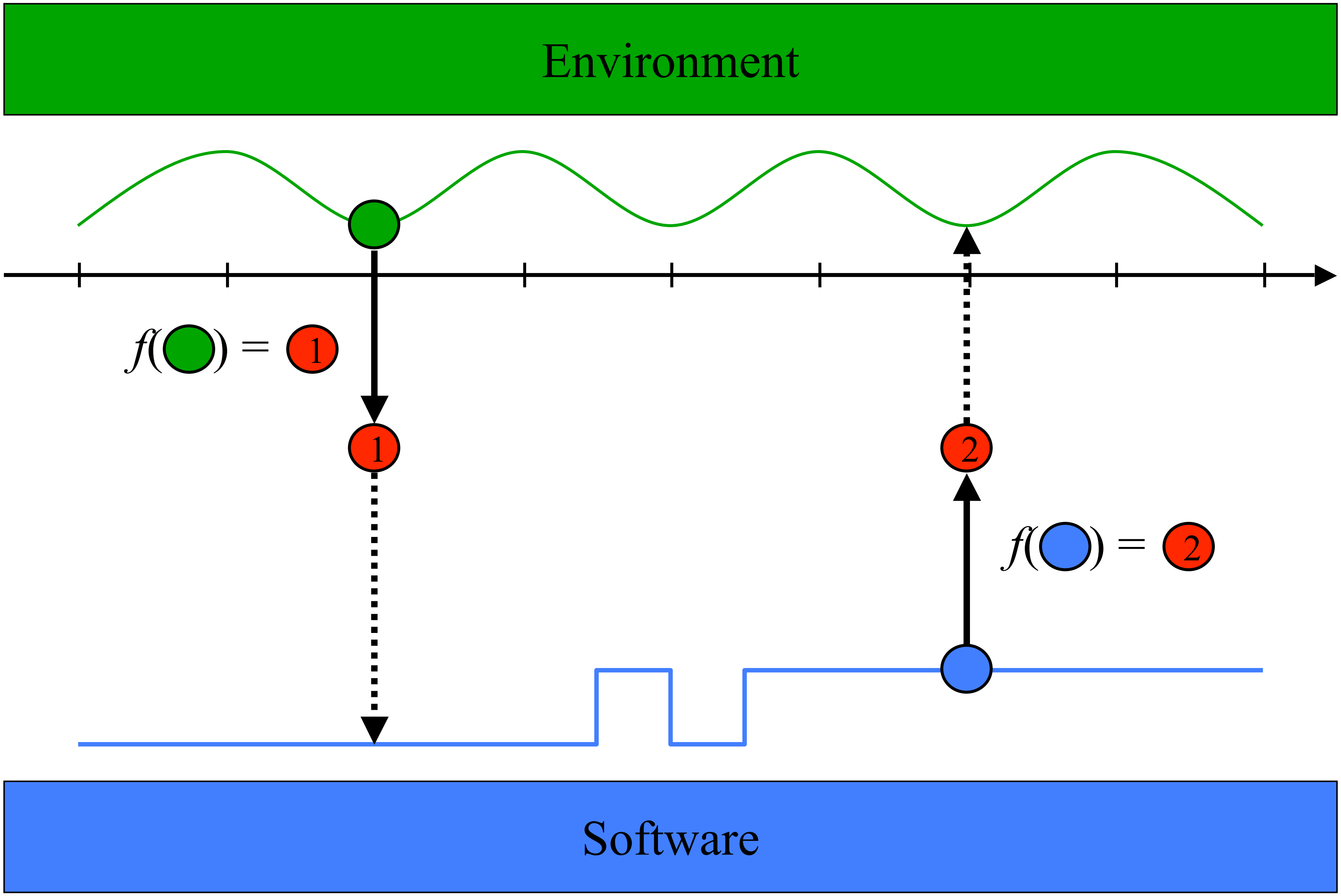
…but Atomic



The Driver Model



Non-preemptable, Synchronous



Environment

f(🟢) = 1

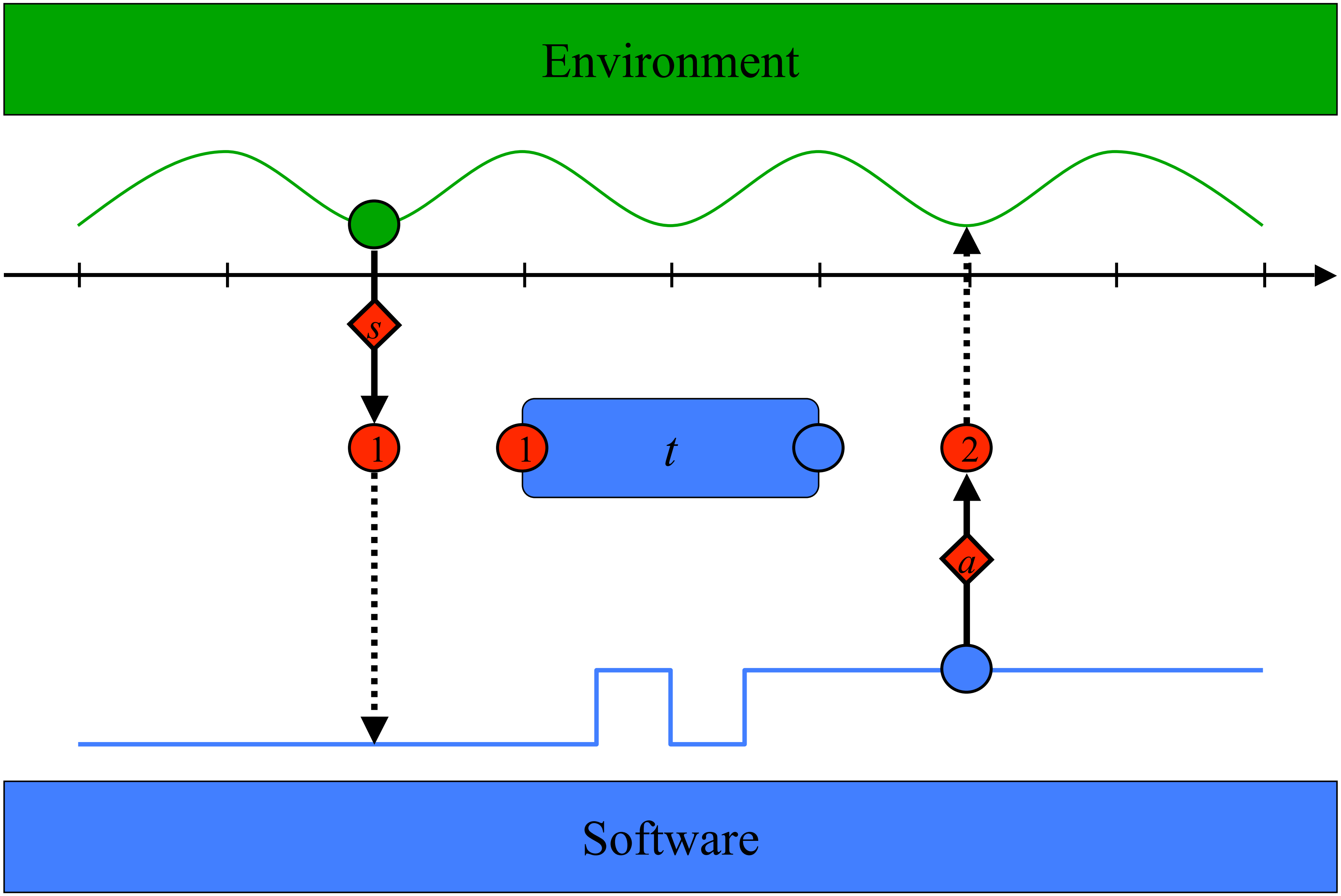
1

2

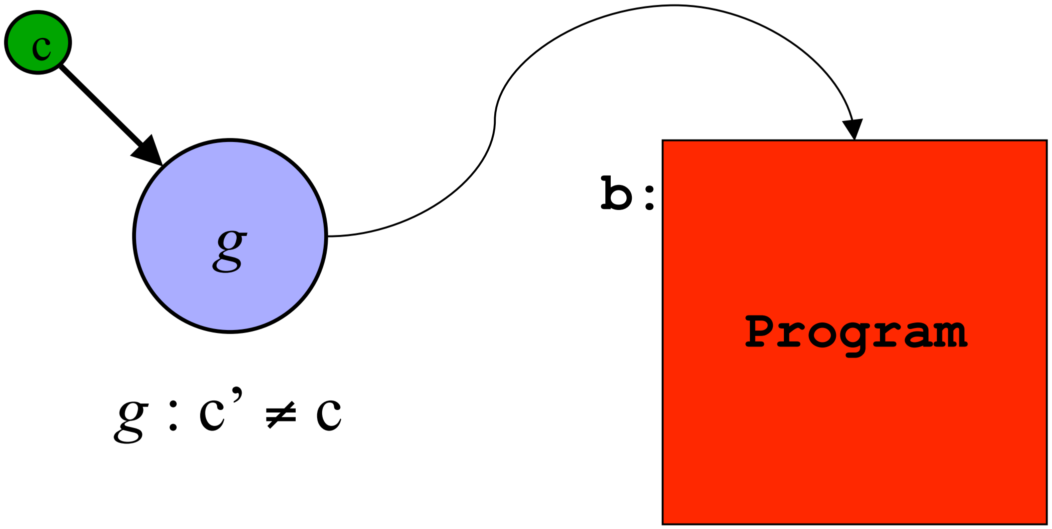
f(🔵) = 2

Software

Syntax

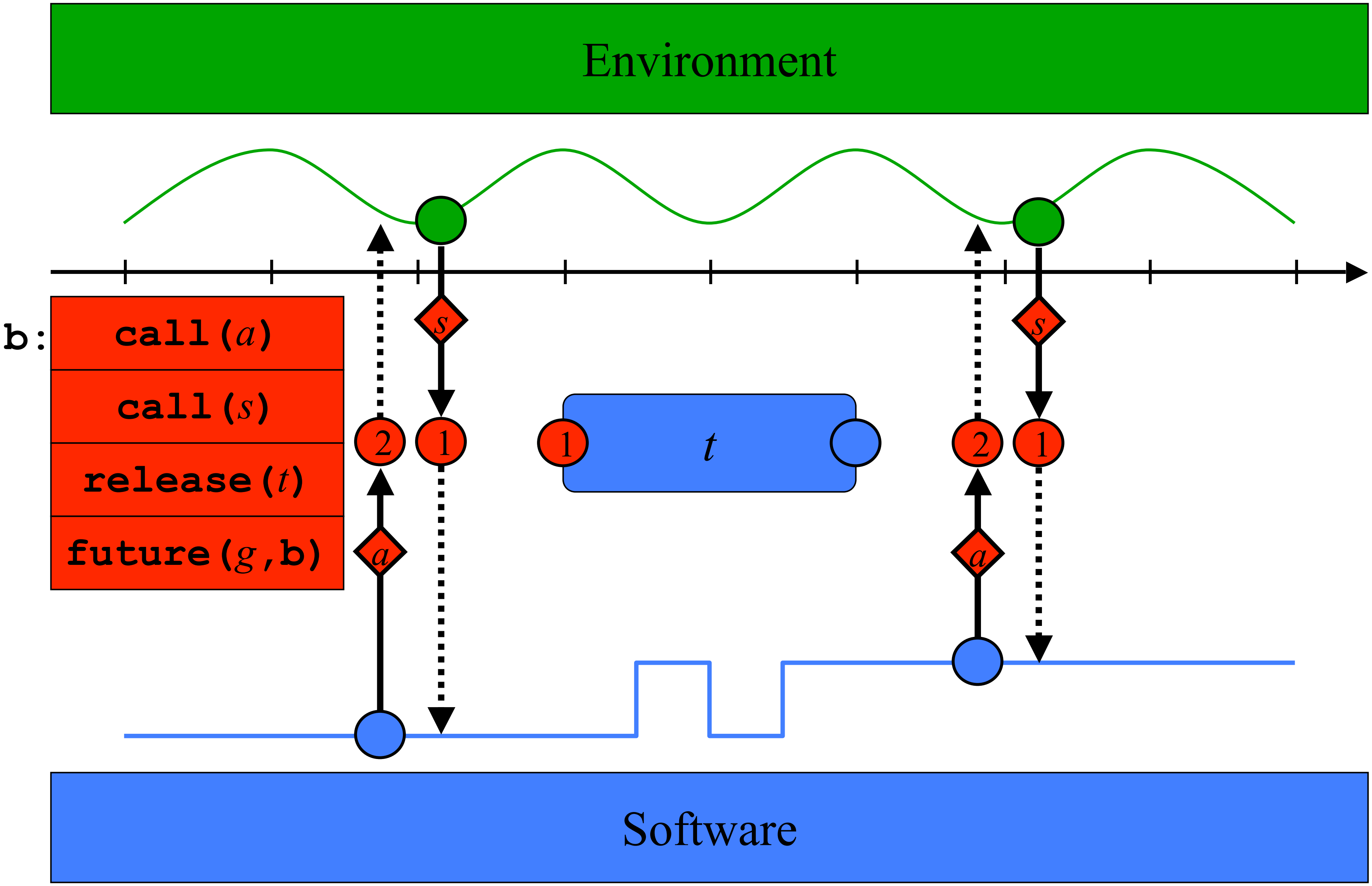


A Trigger *g*



g : c’ ≠ c

An Embedded Machine Program

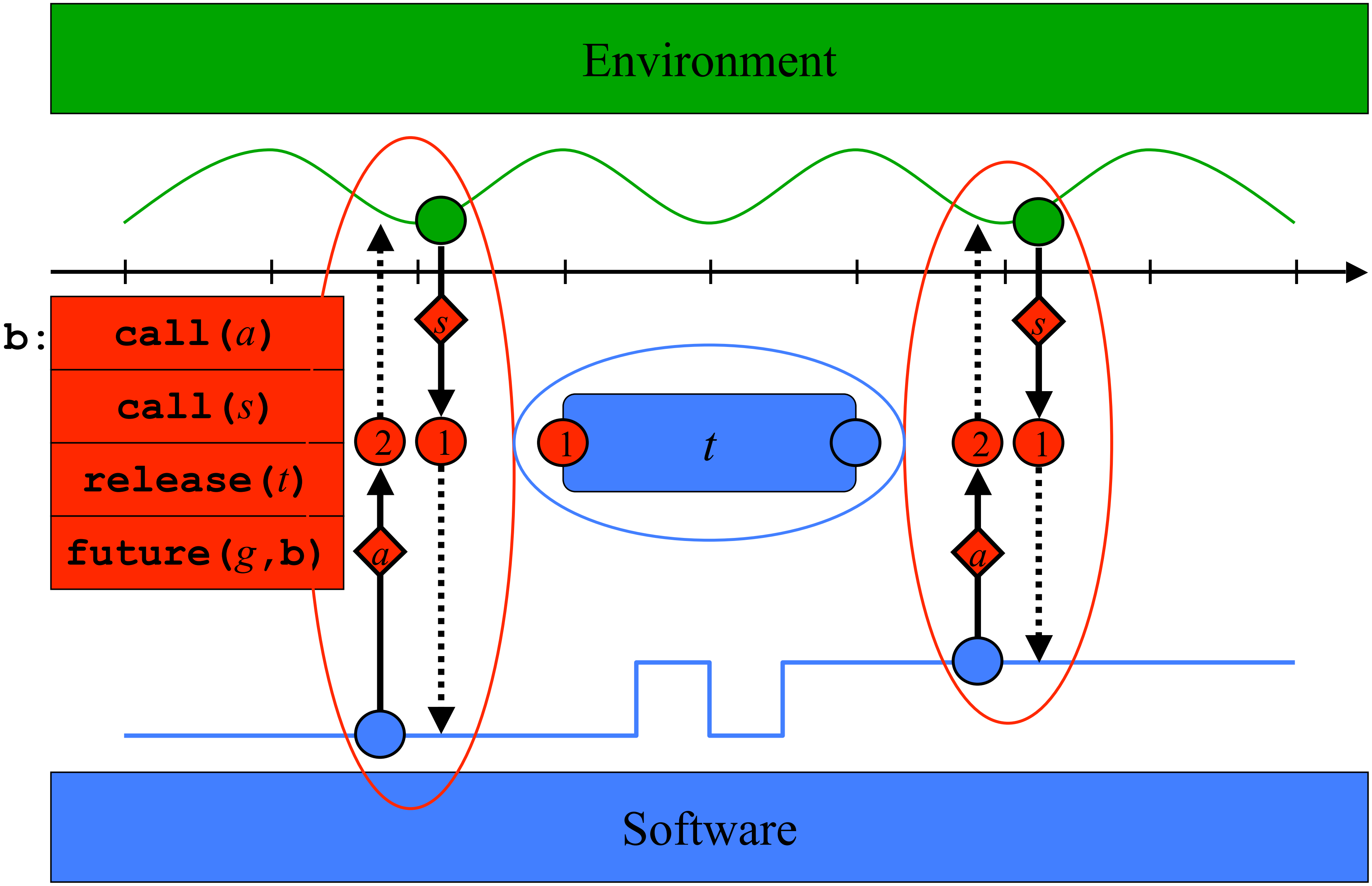


Environment

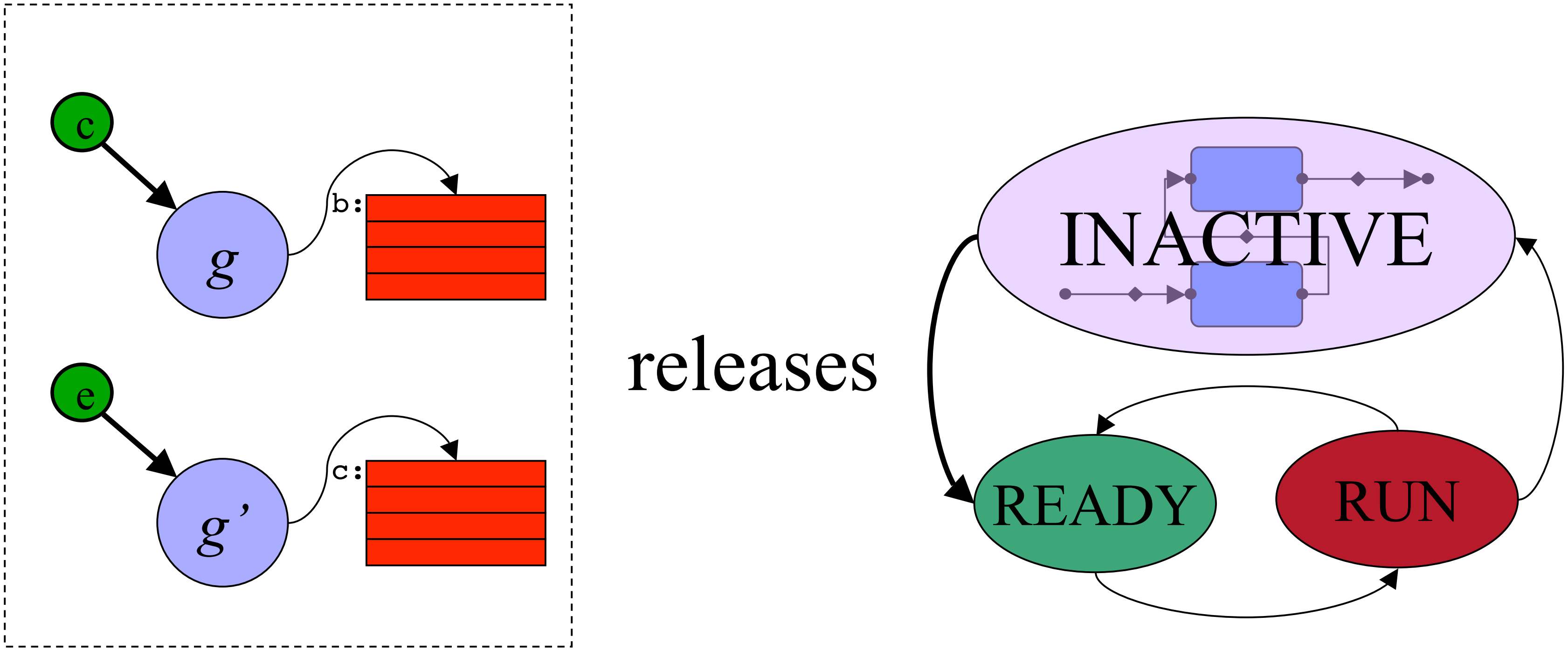
```
b: call(a)
   call(s)
   release(t)
   future(g,b)
```

Software

Synchronous vs. Scheduled Computation



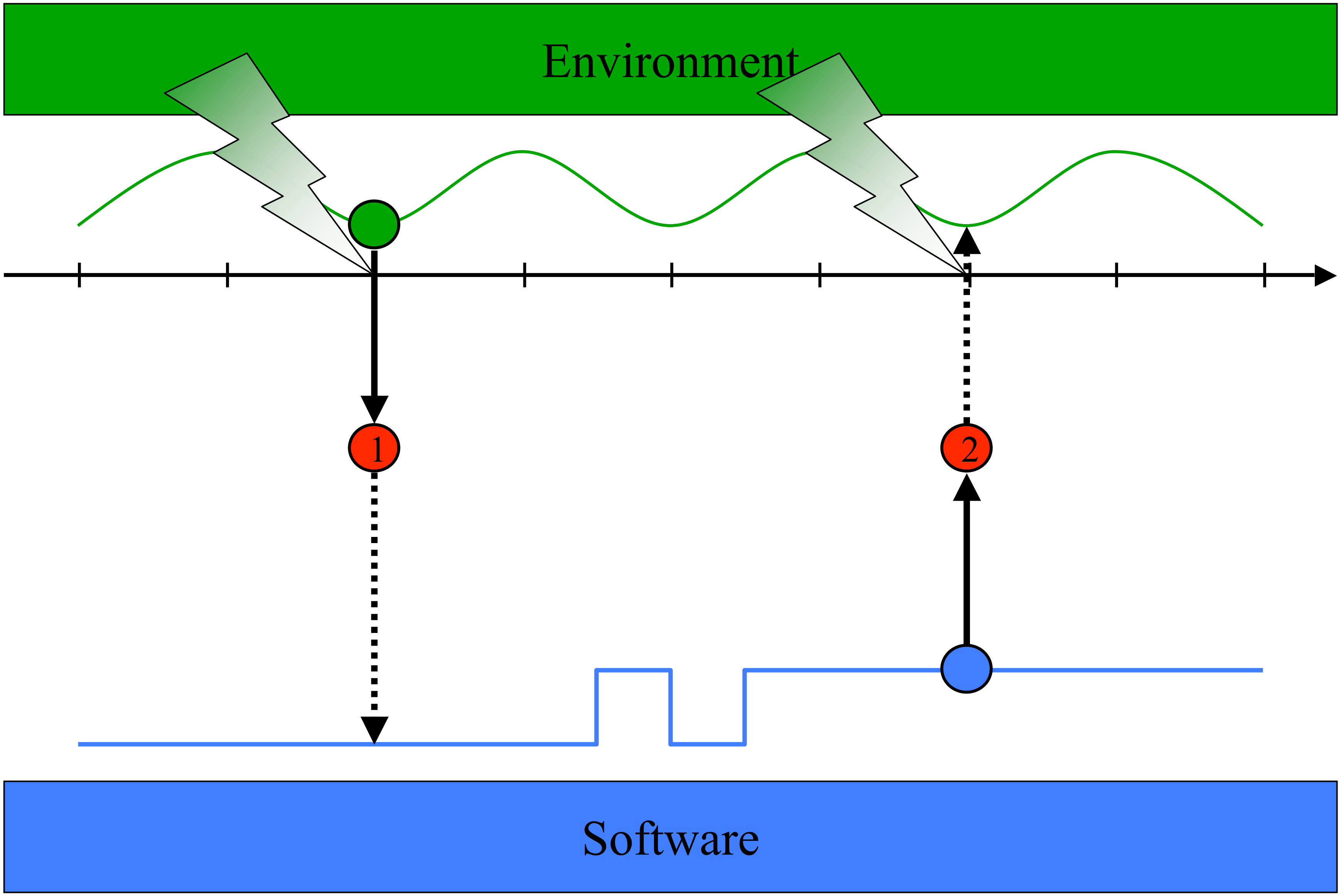
Synchronous vs. Scheduled Computation



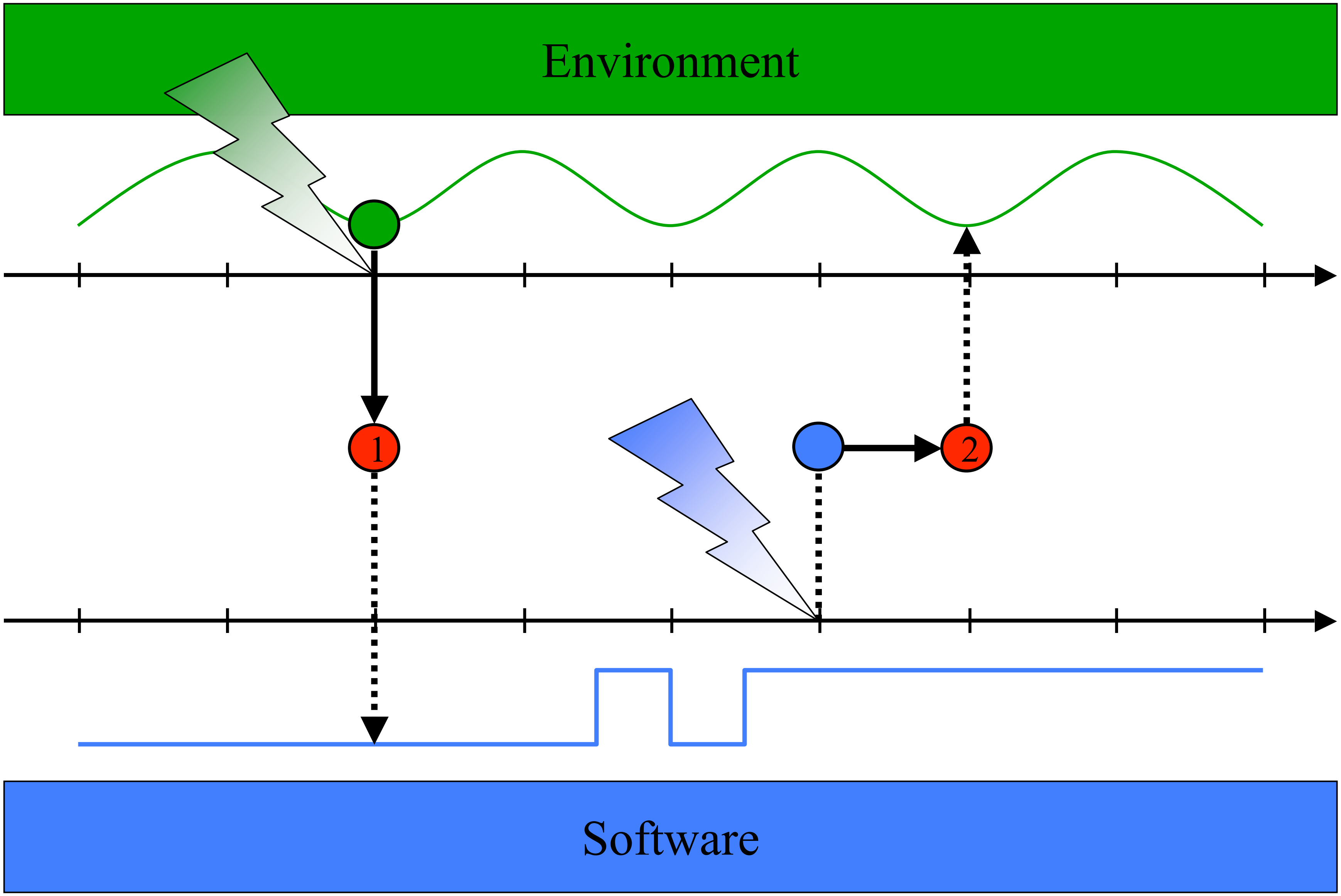
- Synchronous computation
- Kernel context
- Trigger related interrupts disabled

- Scheduled computation
- User context

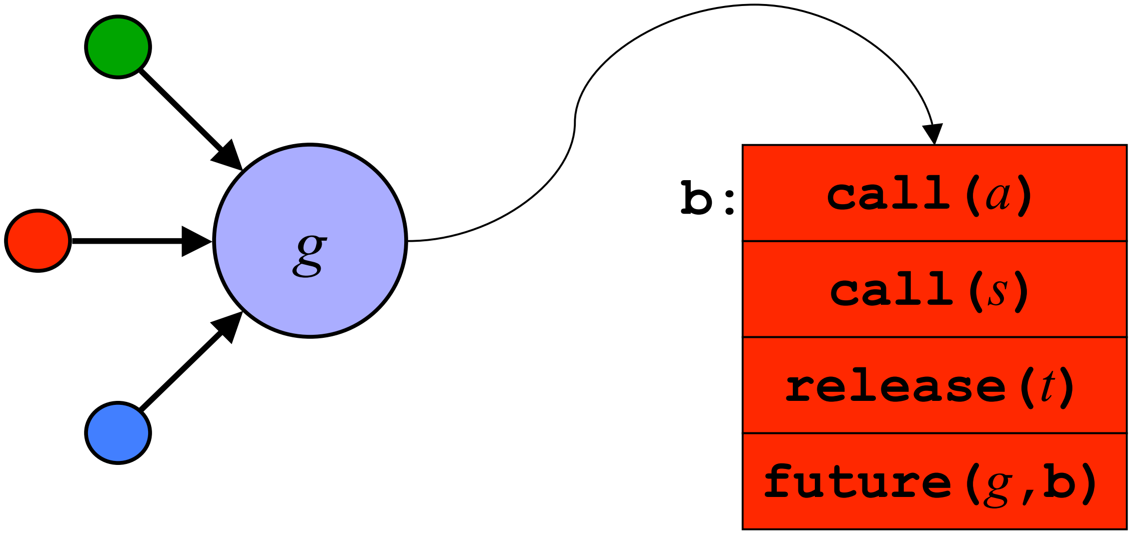
Environment-triggered Code



Software-triggered Code



Trigger *g*: Input-, Environment-Triggered



b:

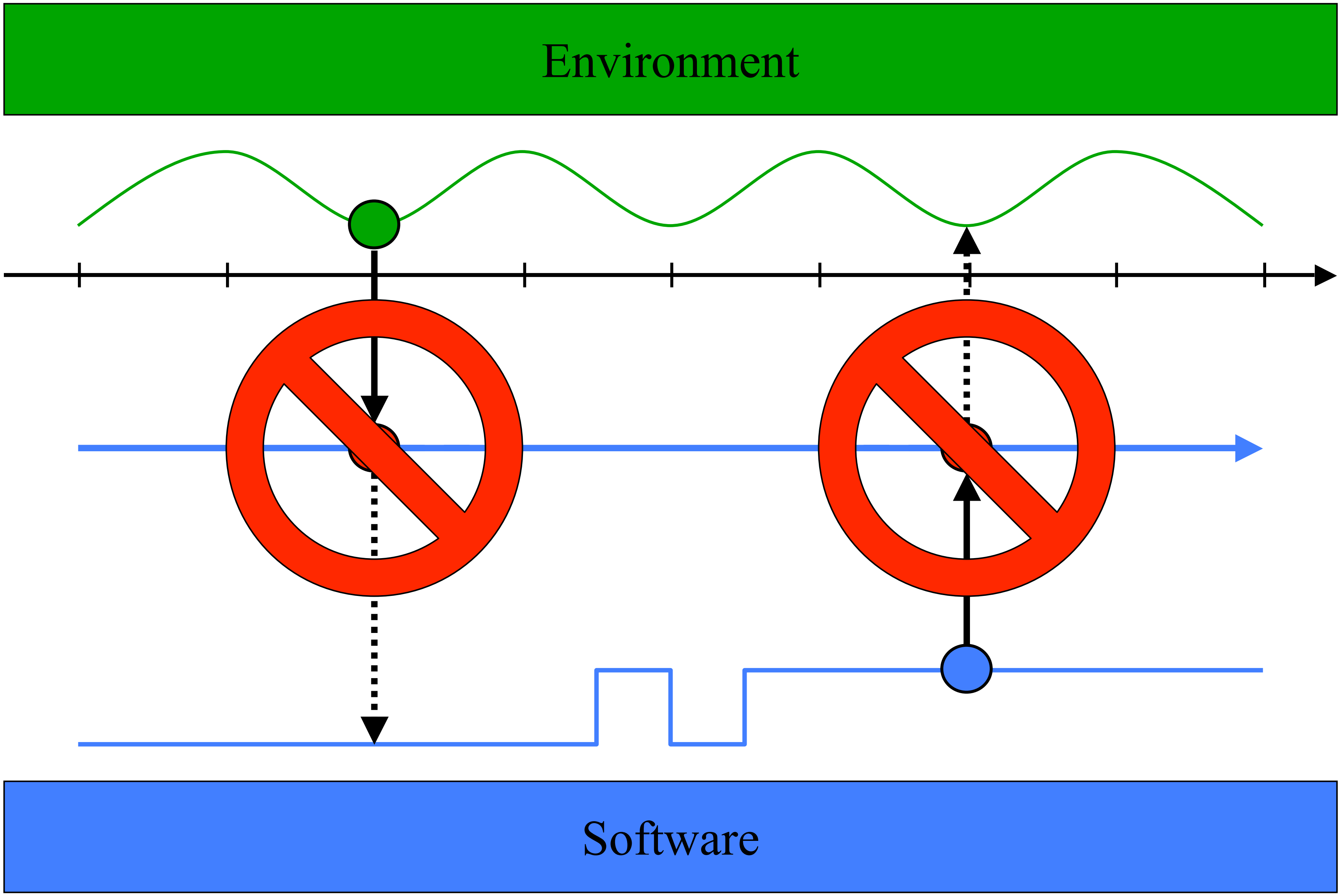
call(*a*)

call(*s*)

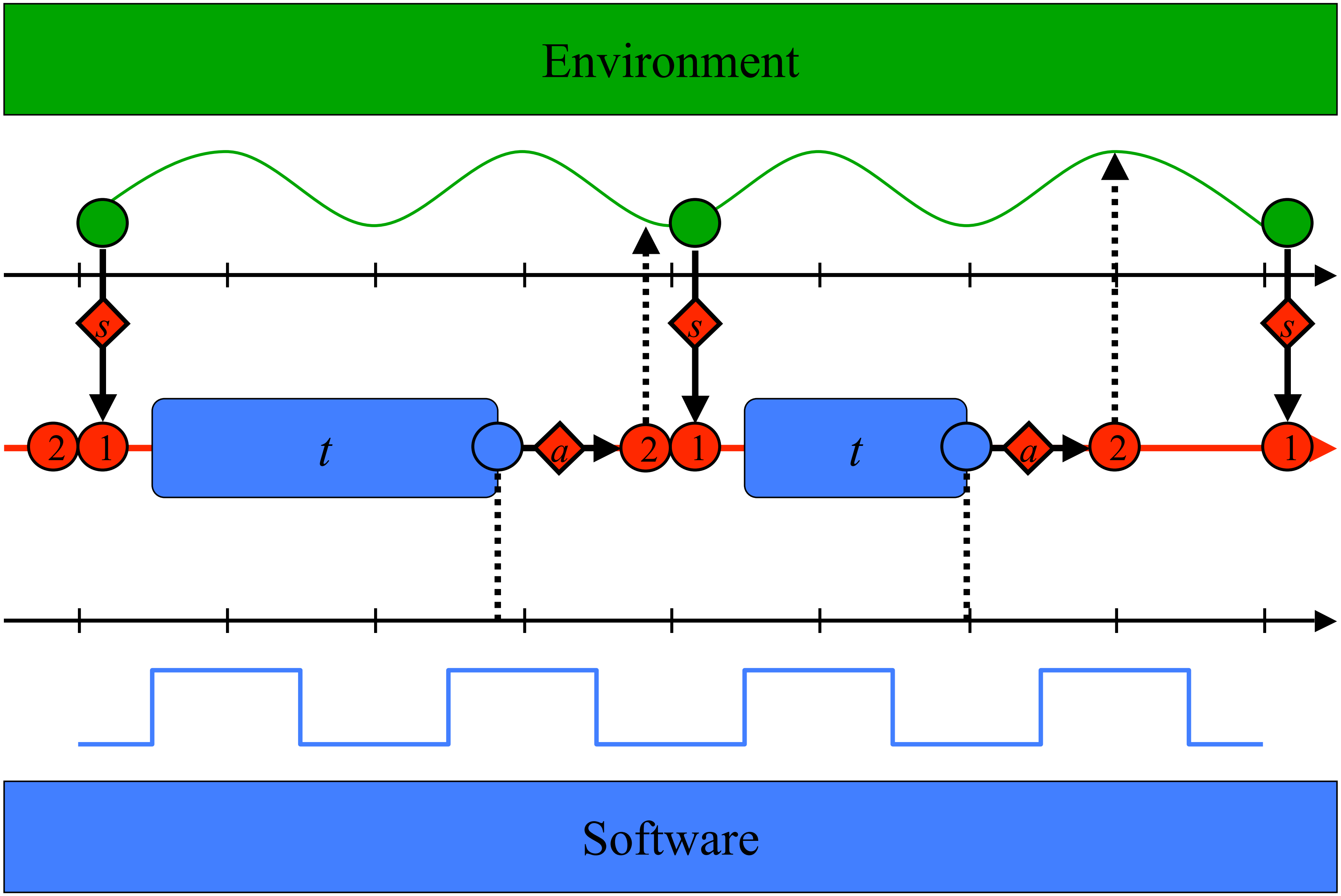
release(*t*)

future(*g*,b)

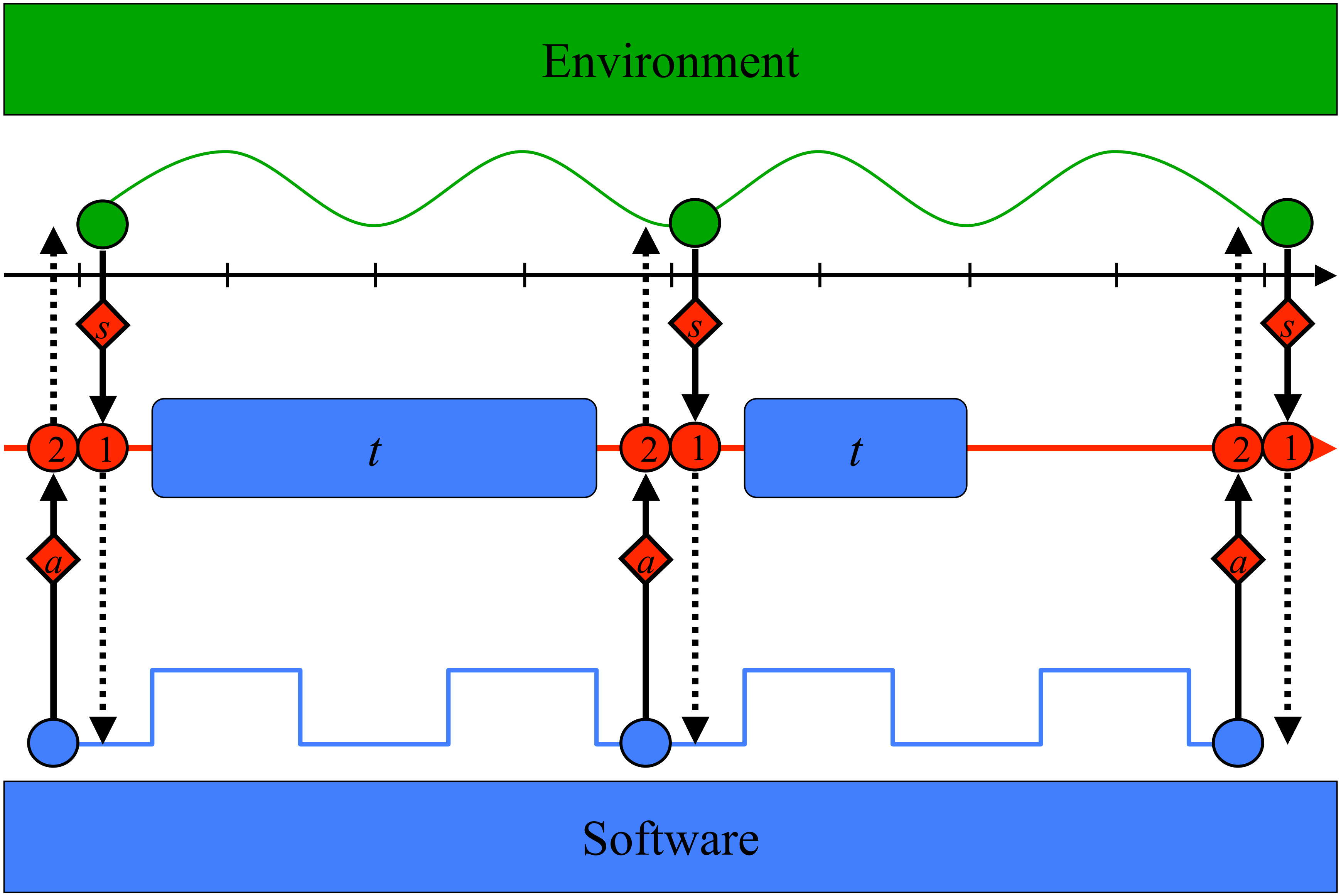
Time Safety



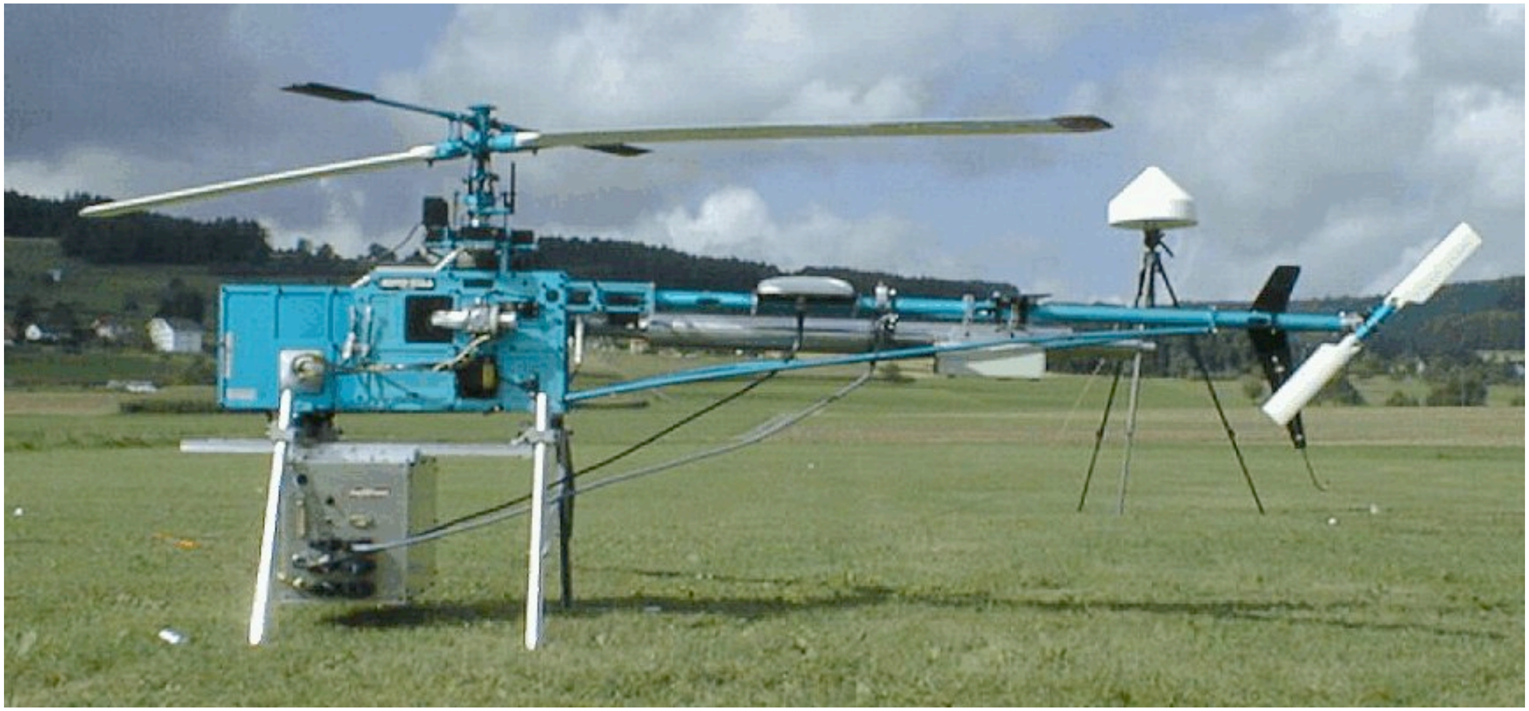
Input-determined If Time Safe



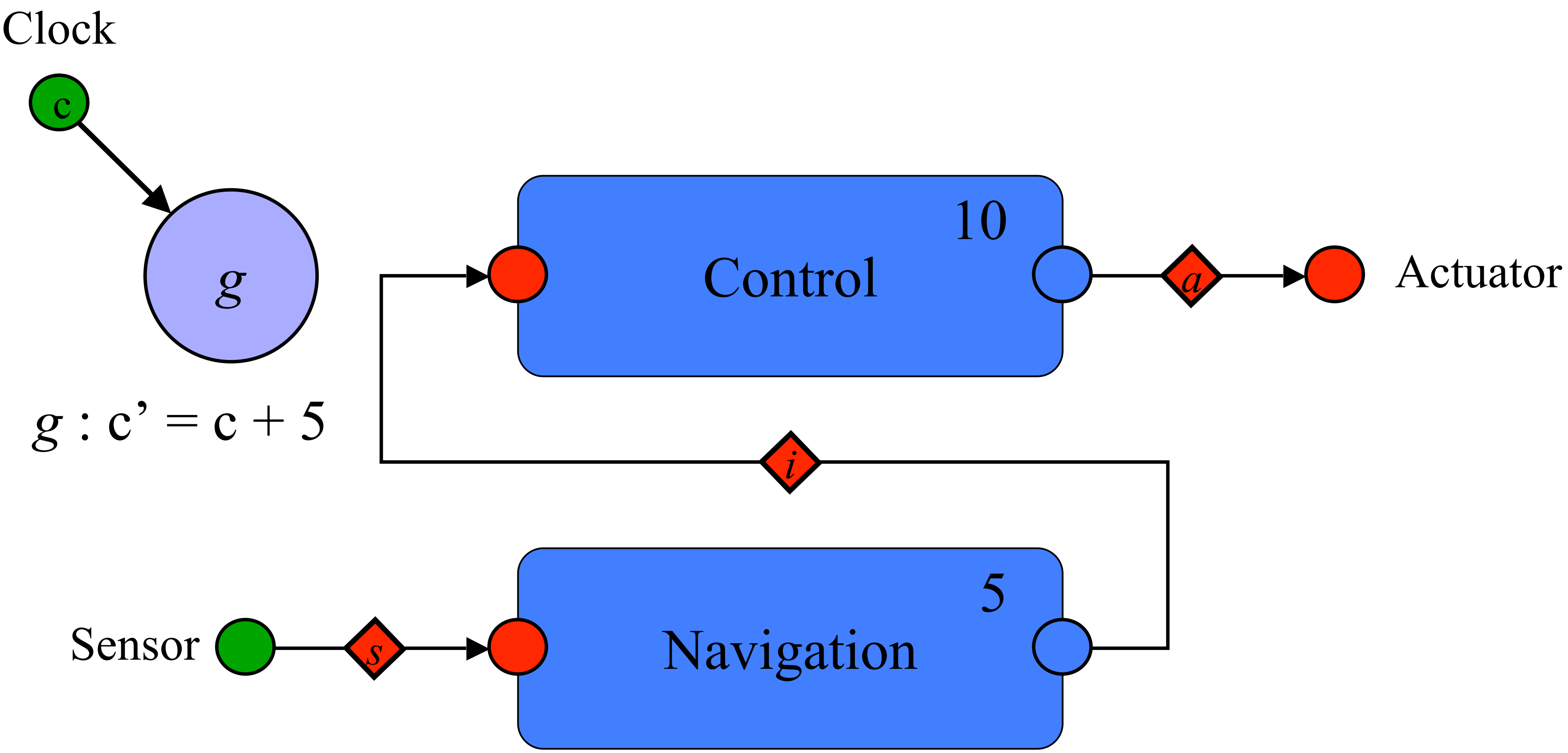
Environment-determined If Environment-triggered



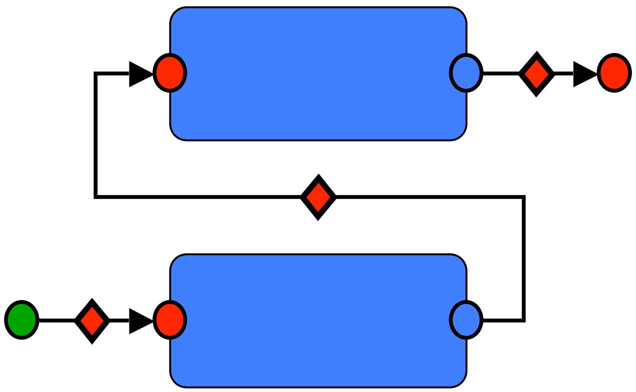
The Zürich Helicopter



Helicopter Control Software

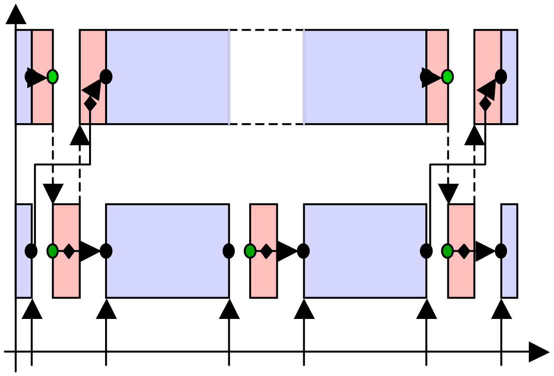


Giotto Syntax (Functionality)



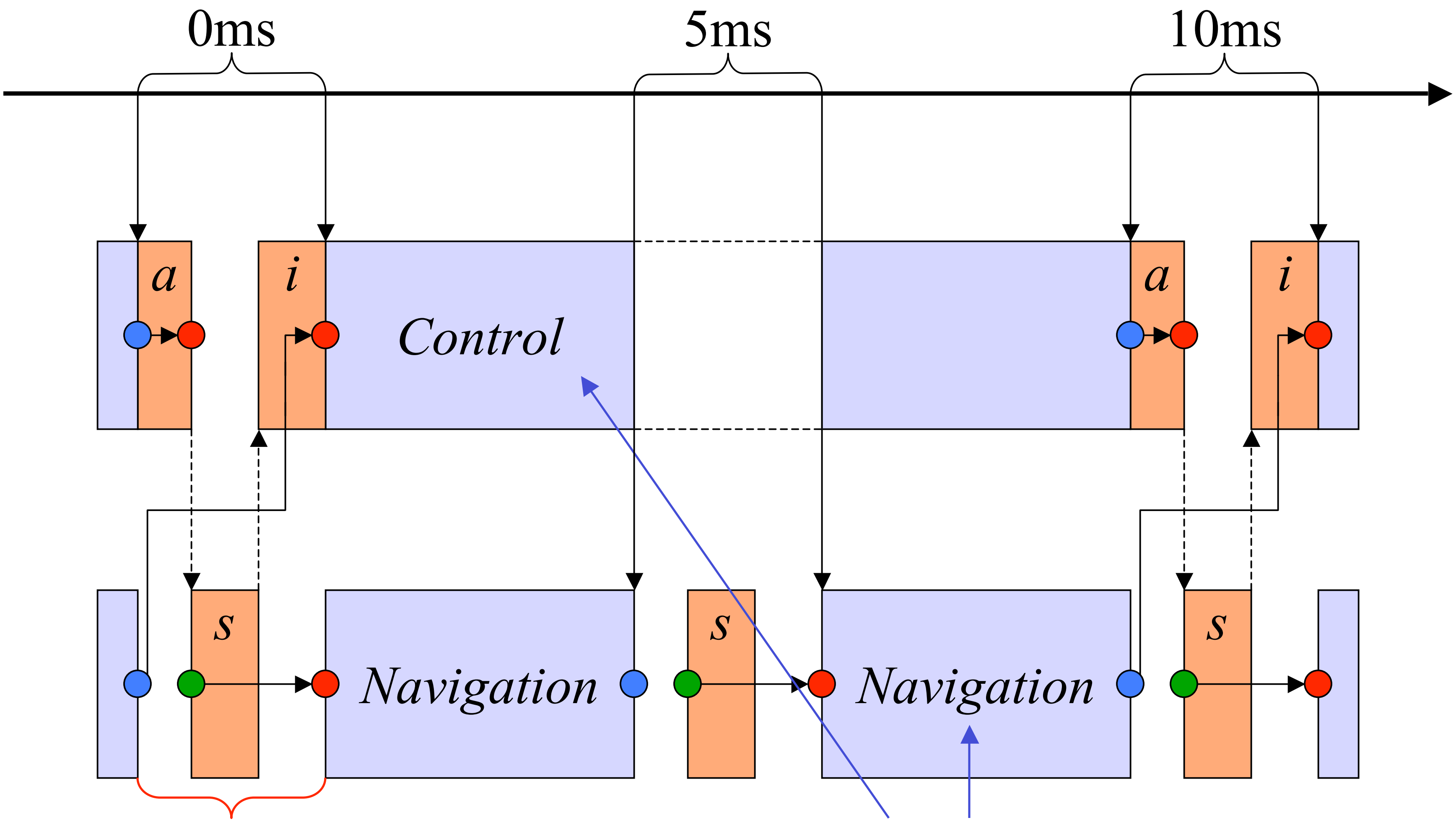
```
sensor gps_type GPS uses c_gps_device ;

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 ) ;
   }
…
```

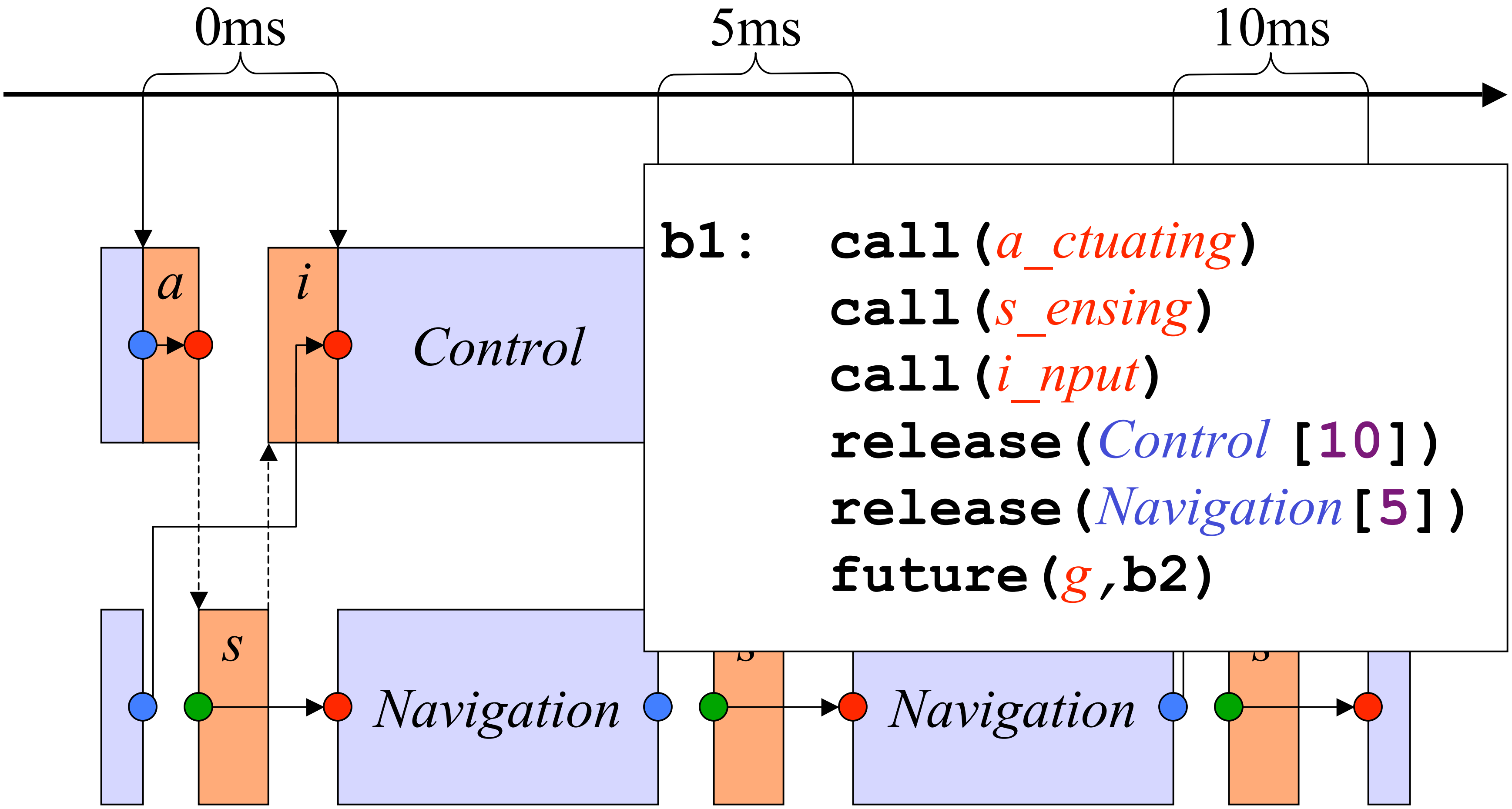
Environment Timeline



Block of synchronous code (nonpreemptable)

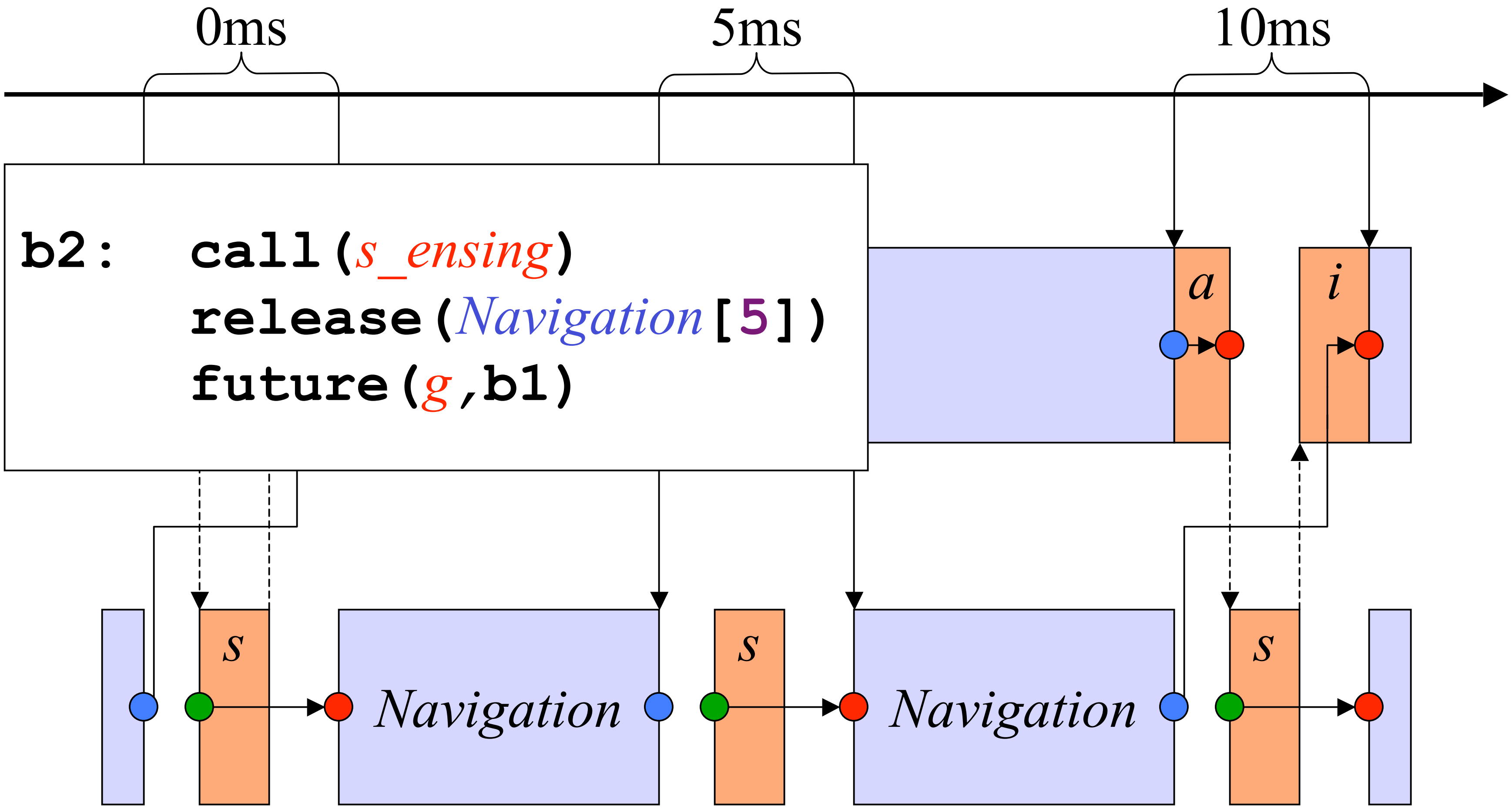
Scheduled tasks (preemptable)

E Code



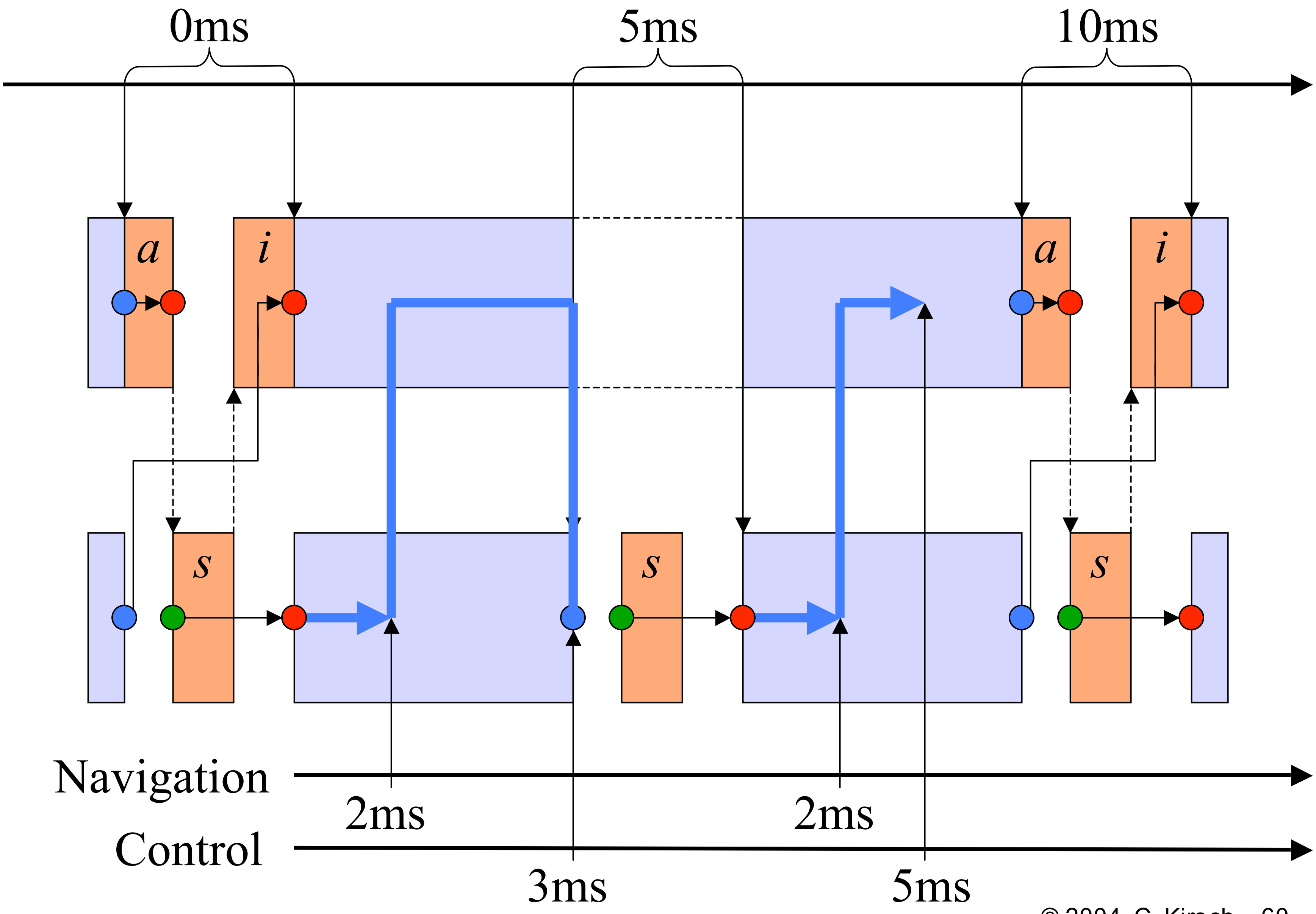
```
b1:   call(a_ctuating)
      call(s_ensing)
      call(i_nput)
      release(Control [10])
      release(Navigation[5])
      future(g,b2)
```

E Code

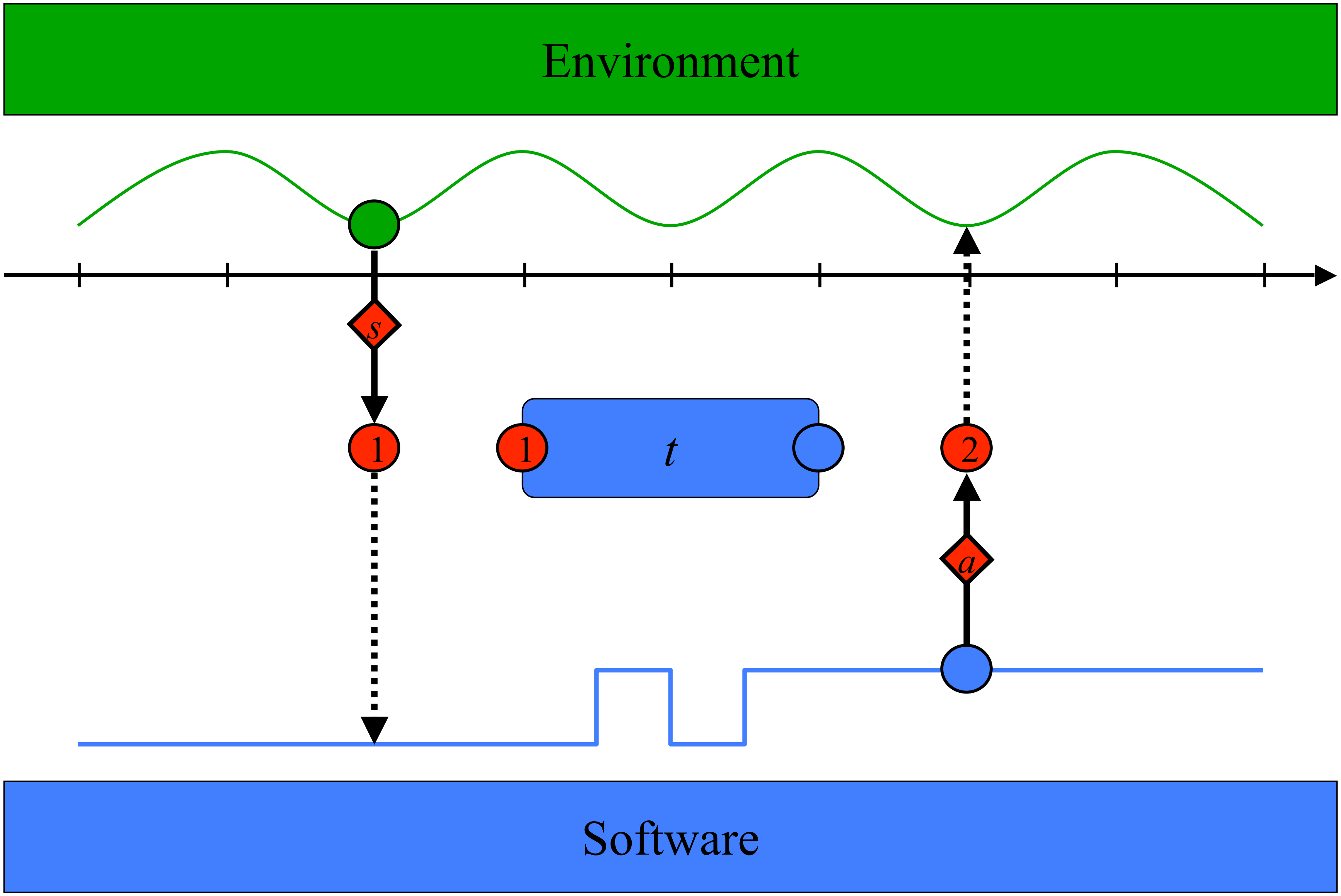


```
b2:   call(s_ensing)
      release(Navigation[5])
      future(g,b1)
```

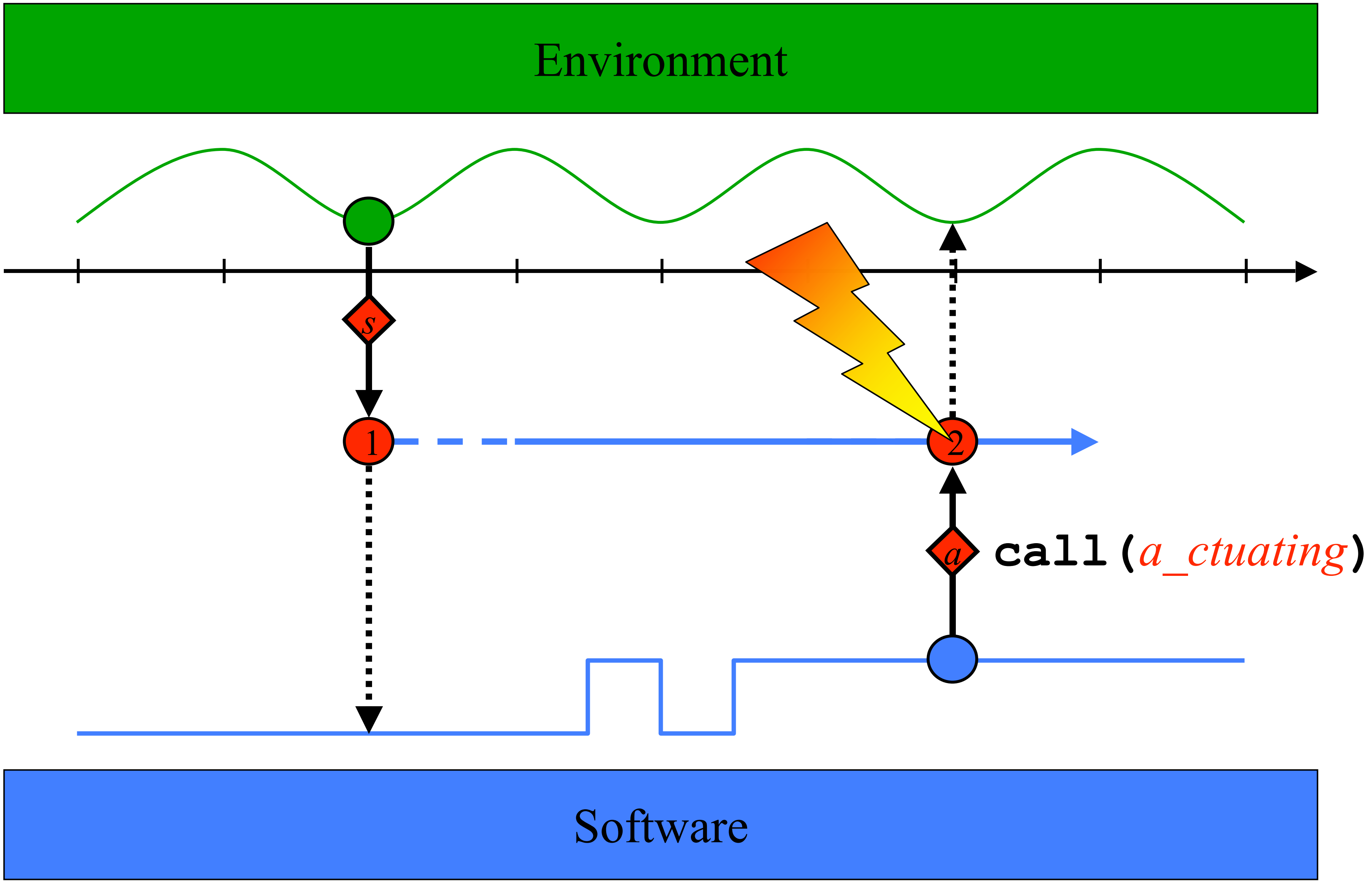
Platform Timeline: EDF



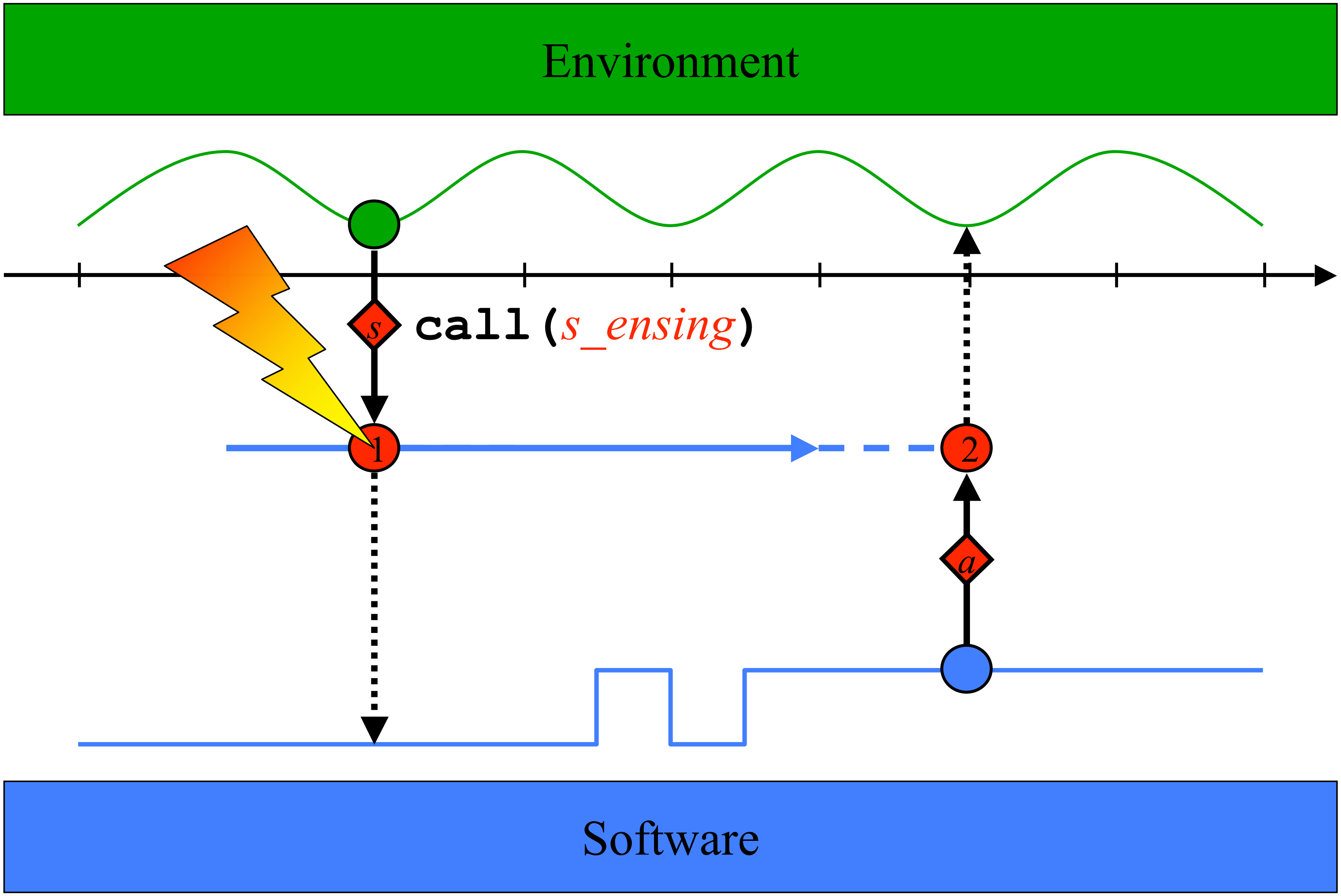
Time Safety



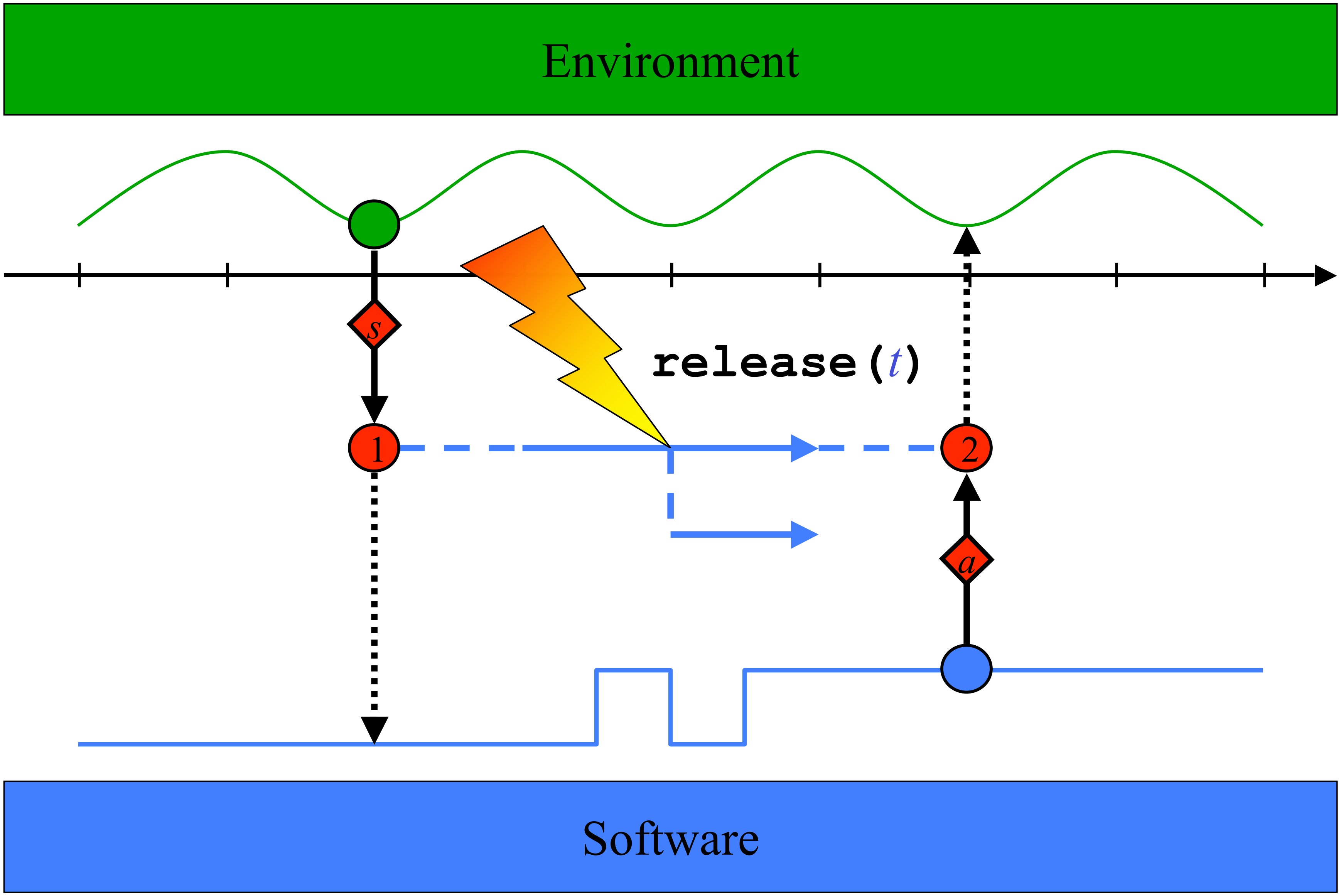
Runtime Exceptions I



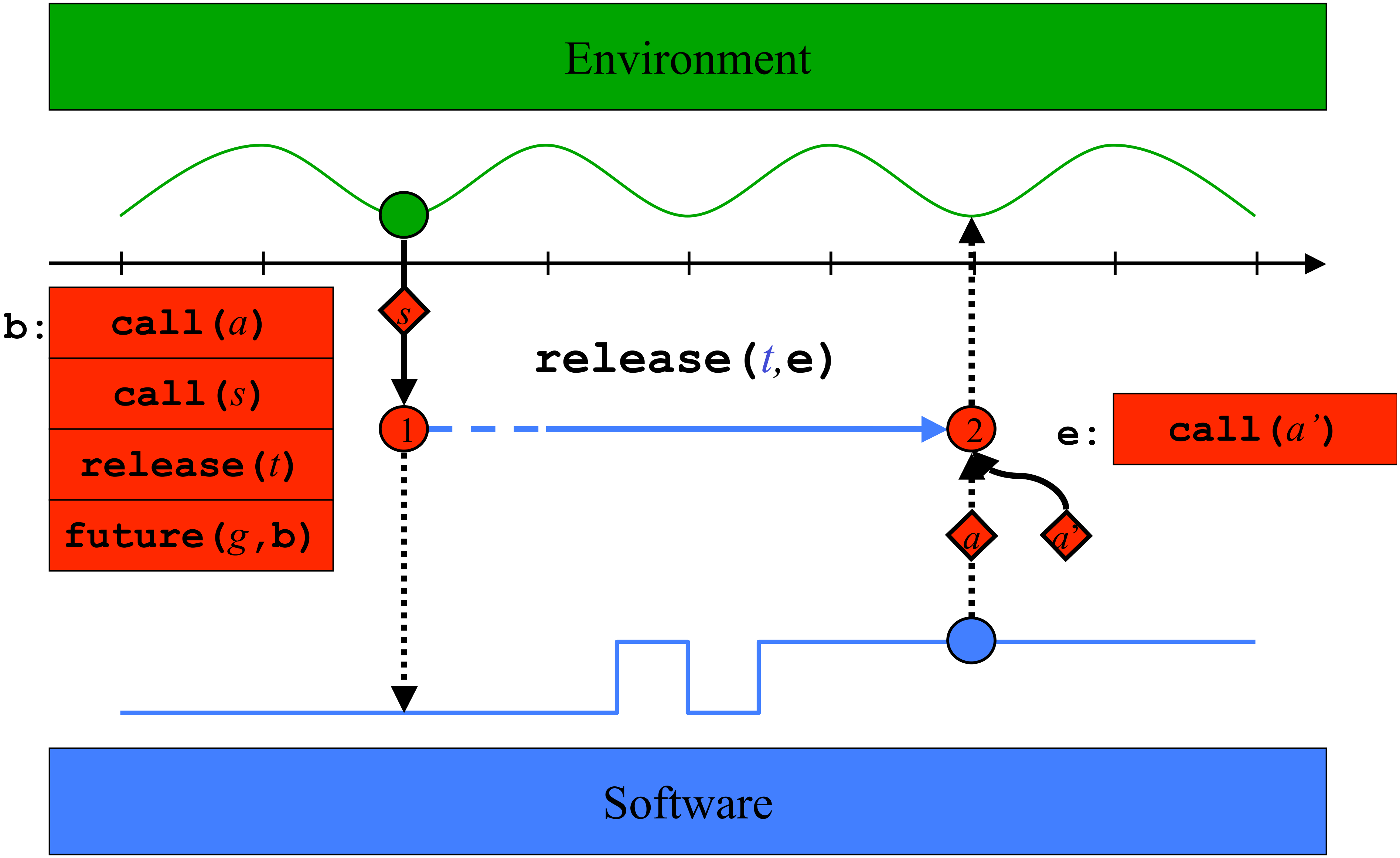
Runtime Exceptions II



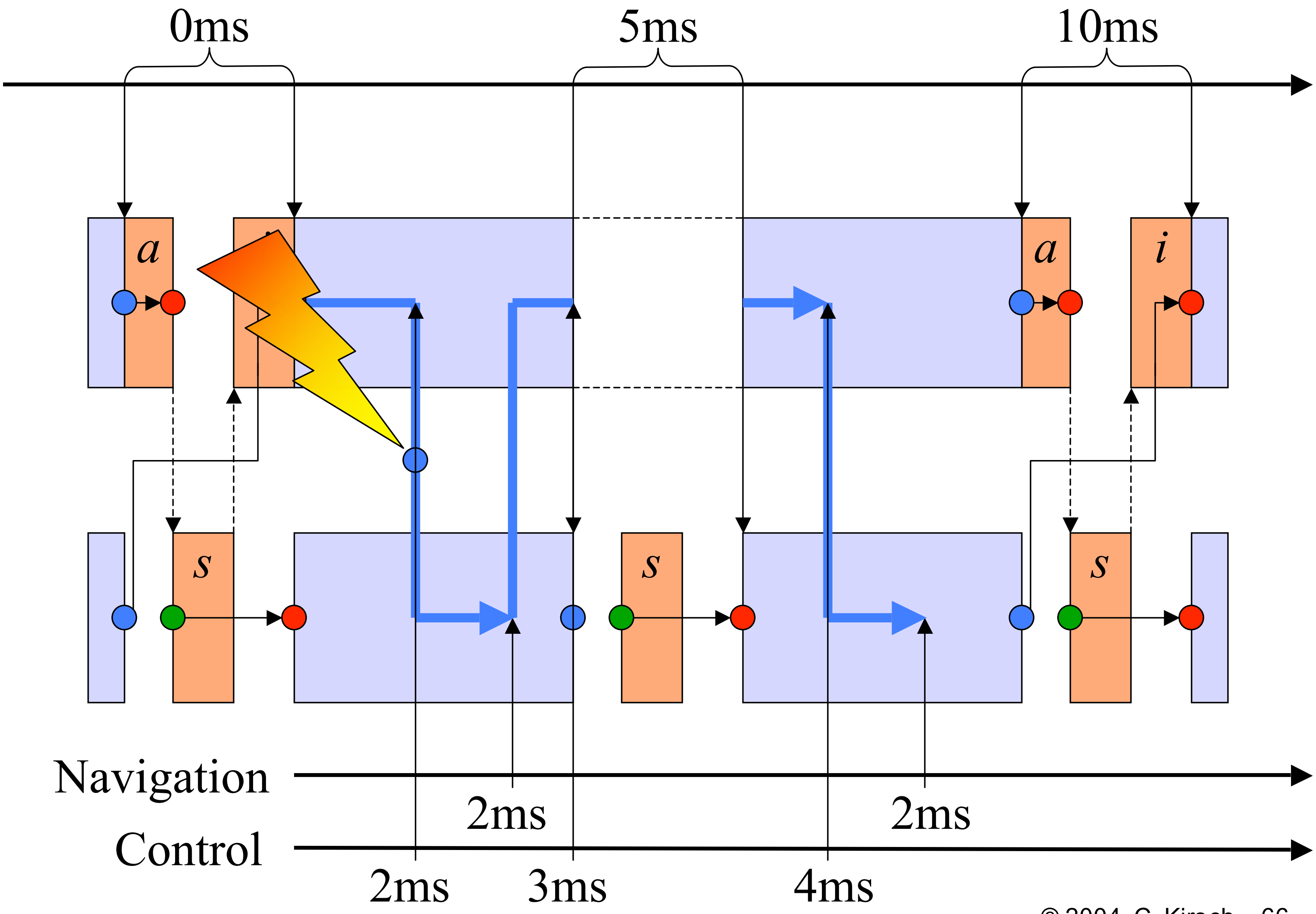
Runtime Exceptions III



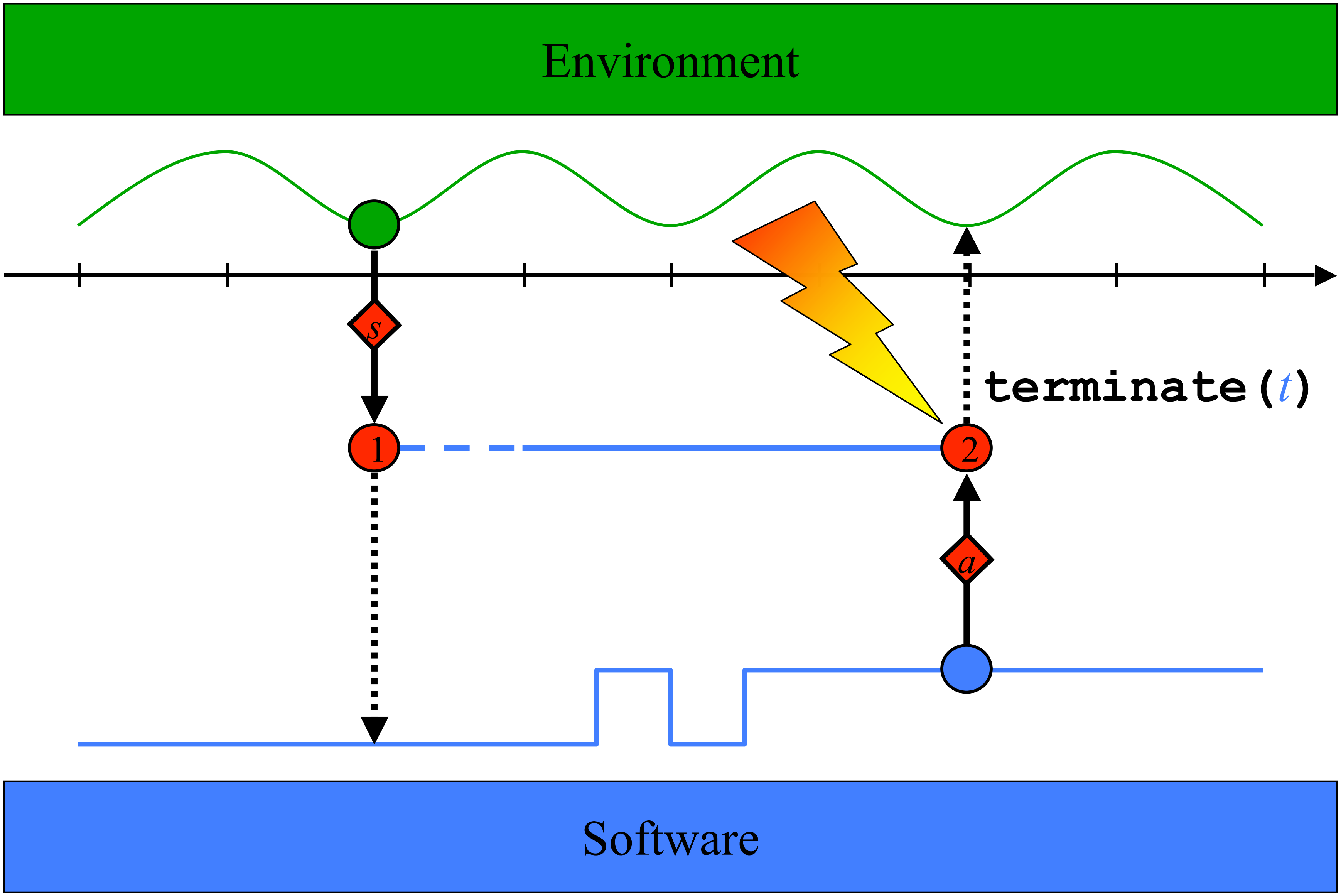
An Exception Handler **e**



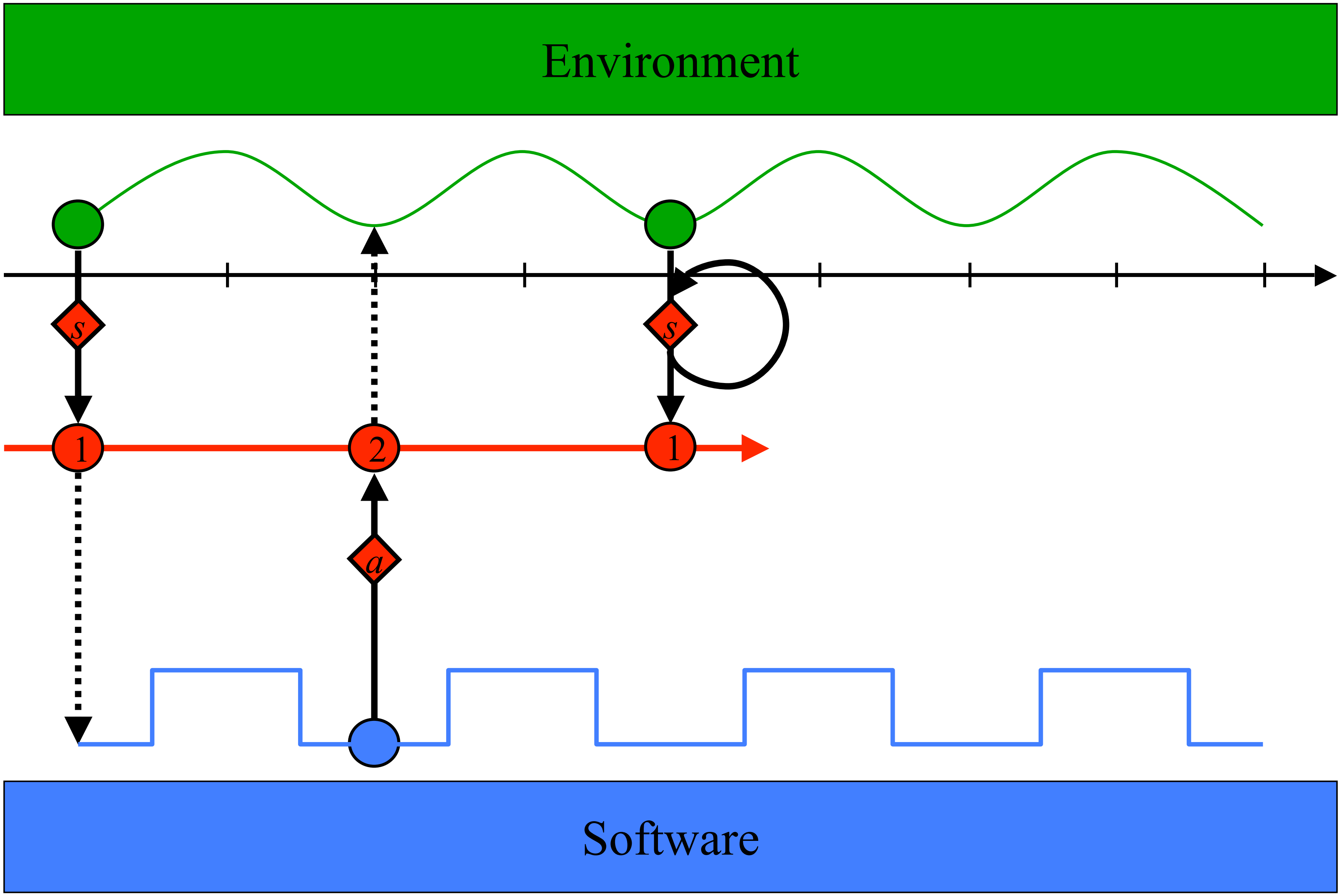
How to Loose Determinism: Task Synchronization



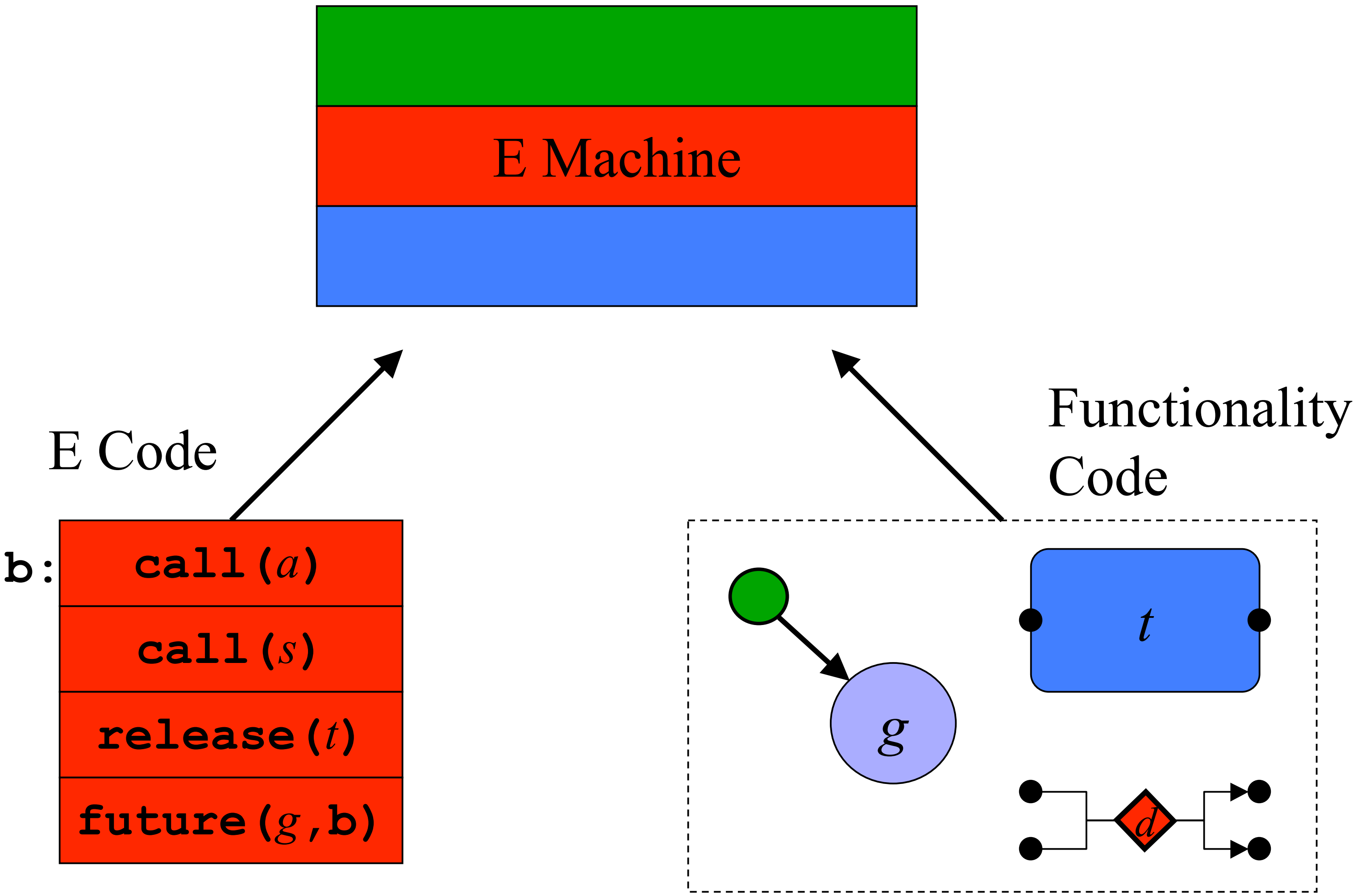
How to Loose Determinism: Termination



Time Liveness: Infinite Traces



Dynamic Linking



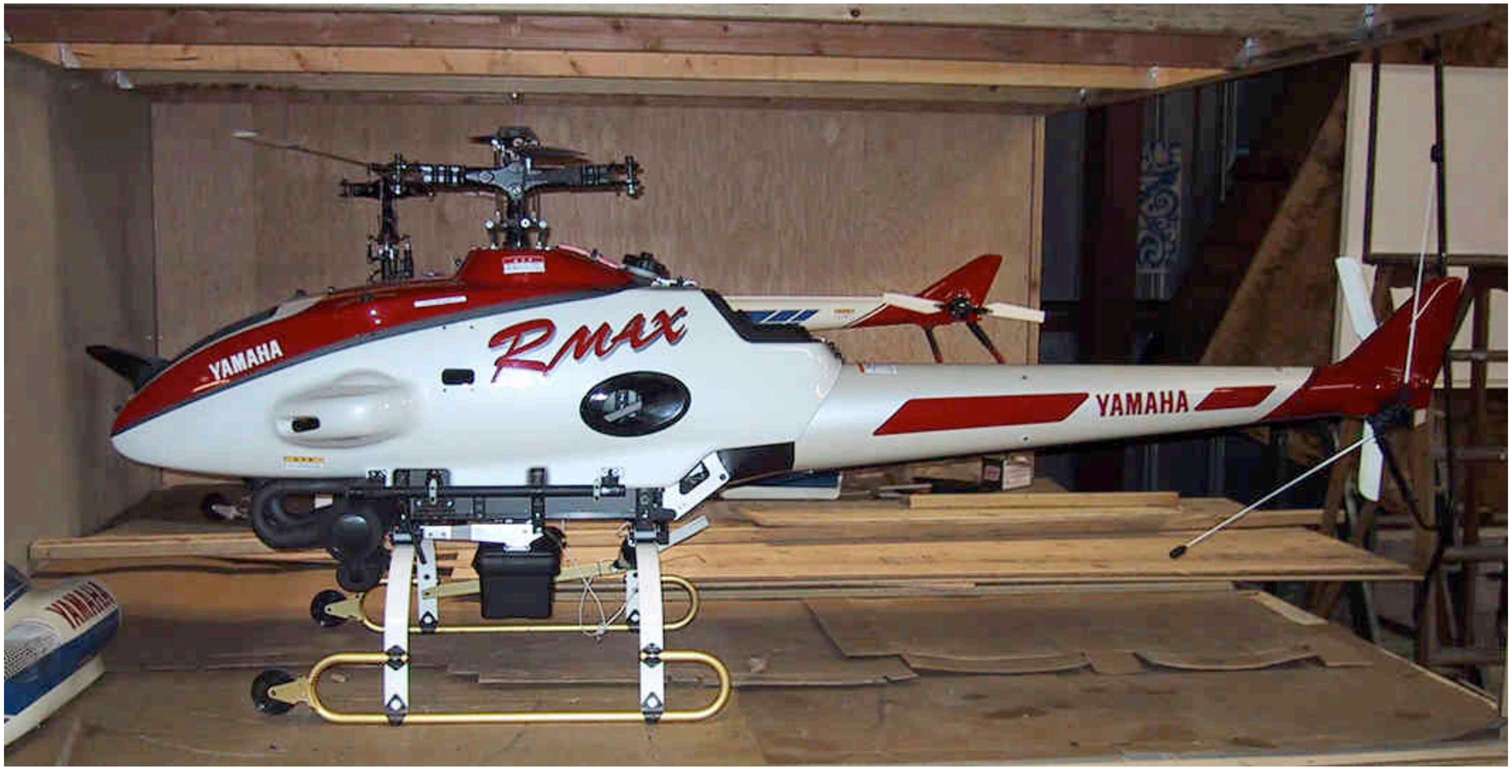
E Machine

E Code

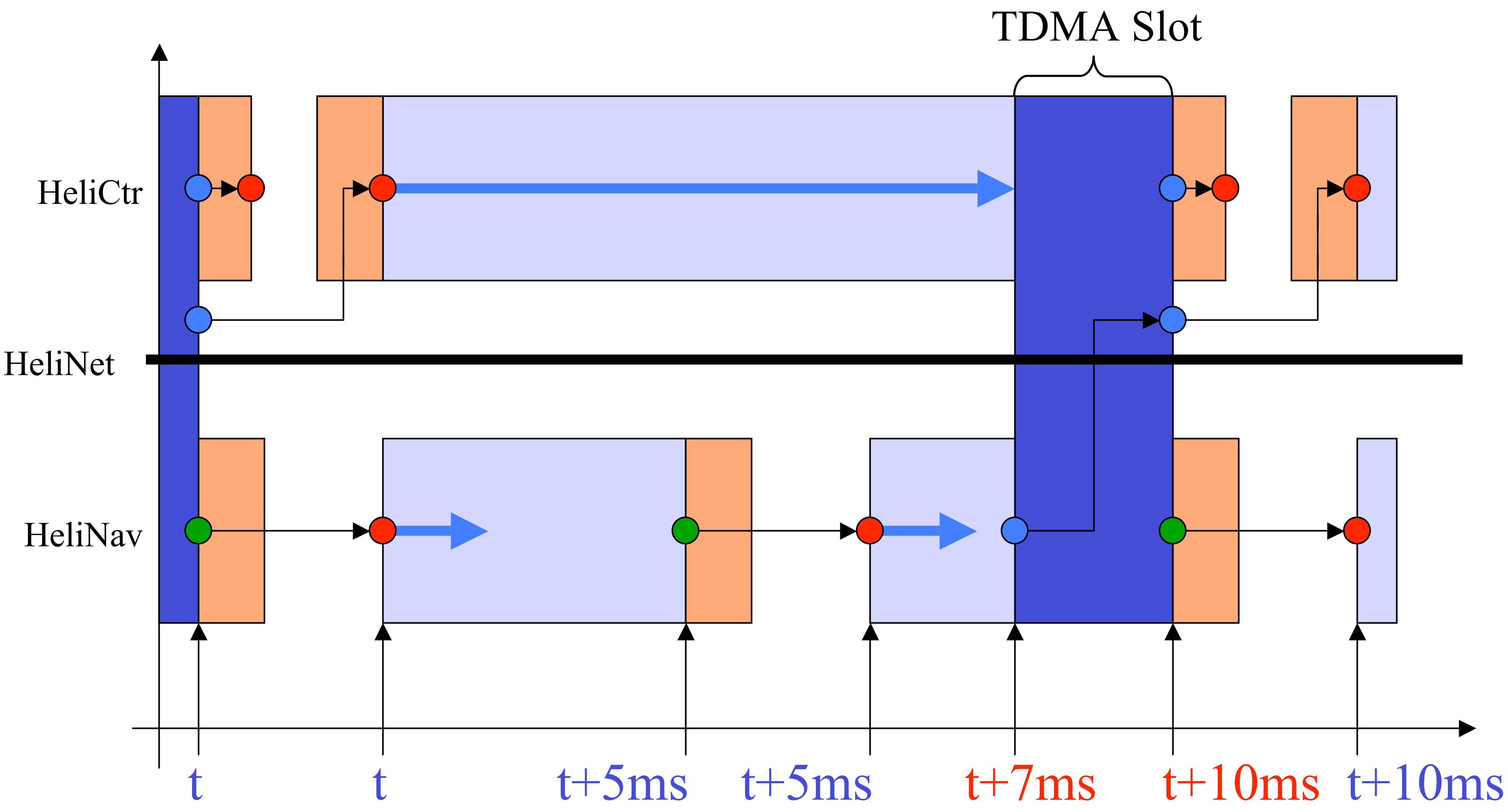
Functionality Code

```
b: call(a)
   call(s)
   release(t)
   future(g,b)
```

The Berkeley Helicopter

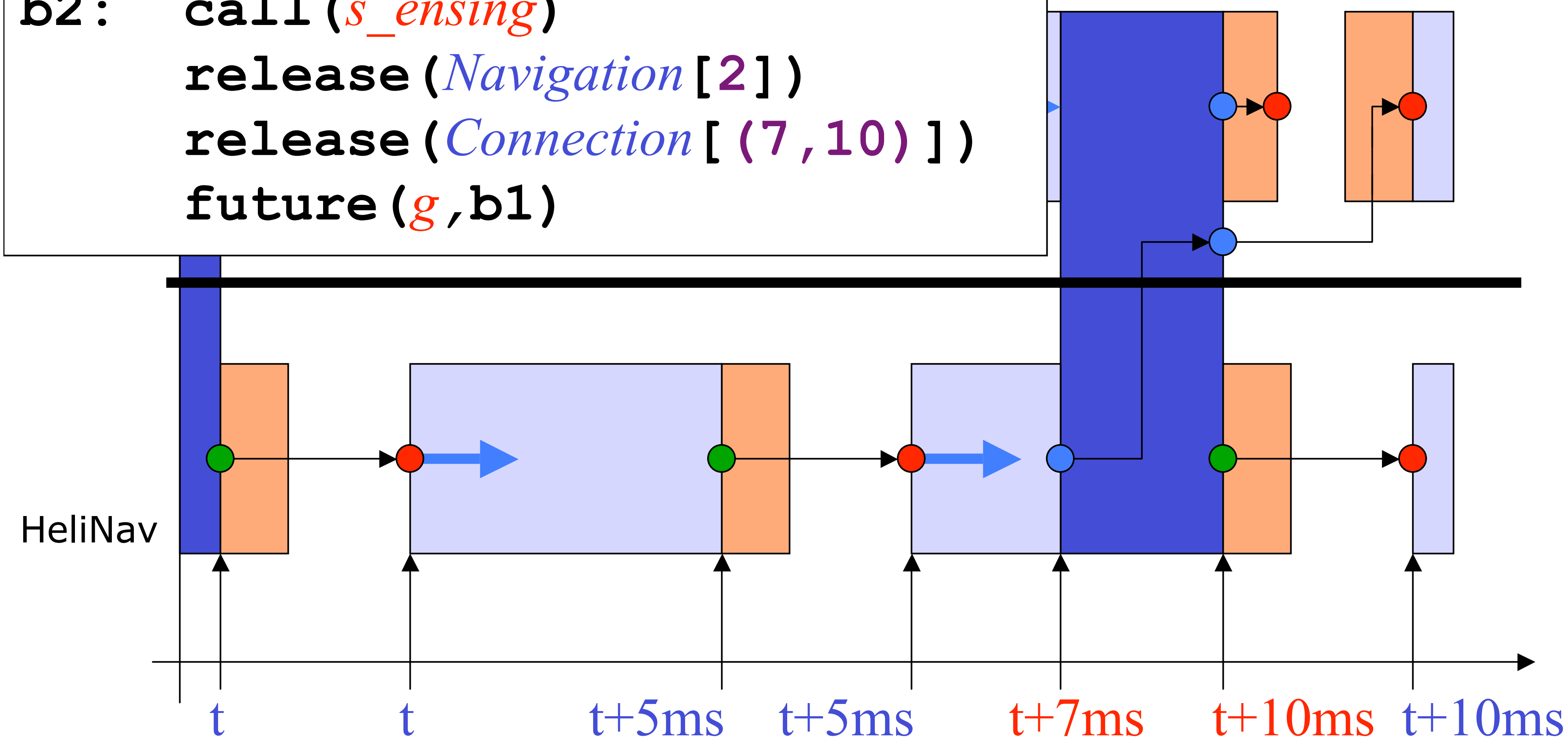


Platform Timeline: Time-triggered Communication



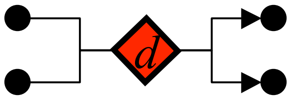
Code Generation for HeliNav

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



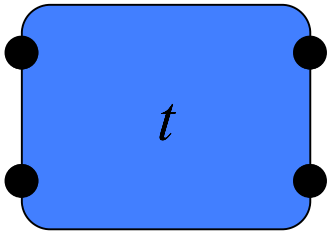
Instructions

Synchronous Driver:



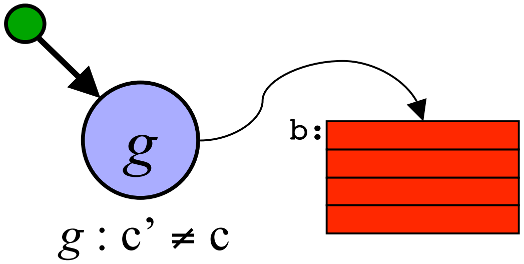
call(*d*)

Scheduled Task:



release(*t*)

Triggering:



future(*g*,**b**)