Embedded Software Engineering

3 Unit Course, Spring 2002

EECS Department, UC Berkeley

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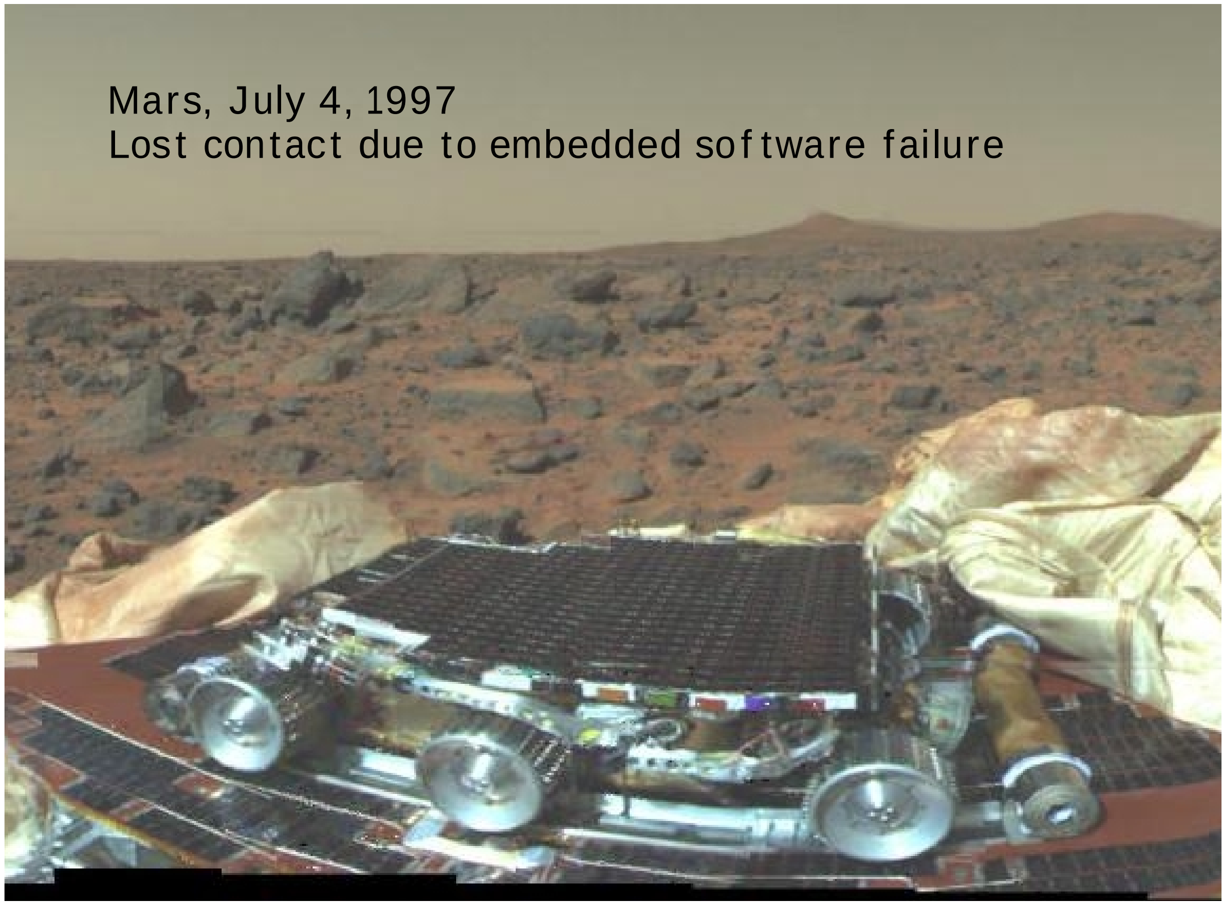
www.eecs.berkeley.edu/~fresco/giotto/course-2002

It’s significant

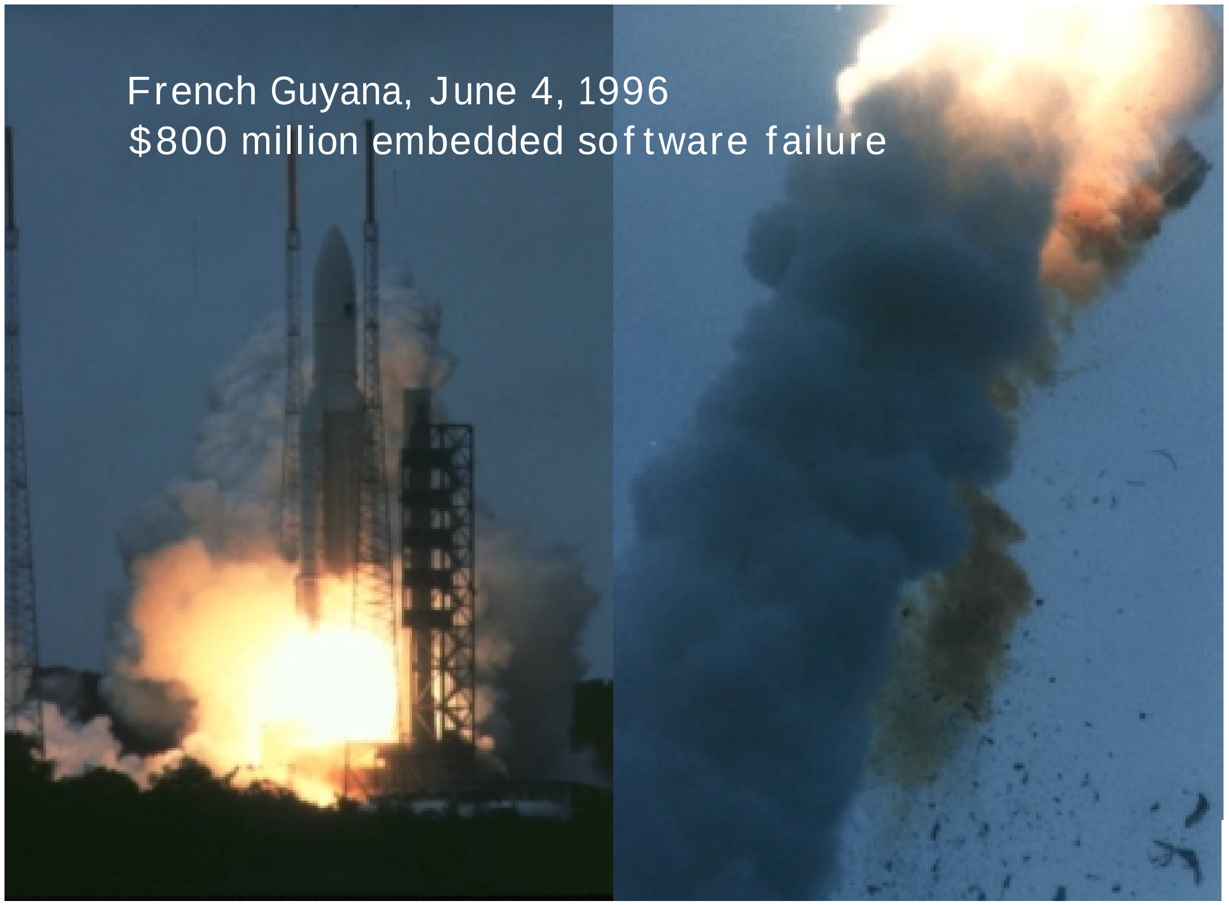
$4 billion development effort

> 50% system integration & validation cost

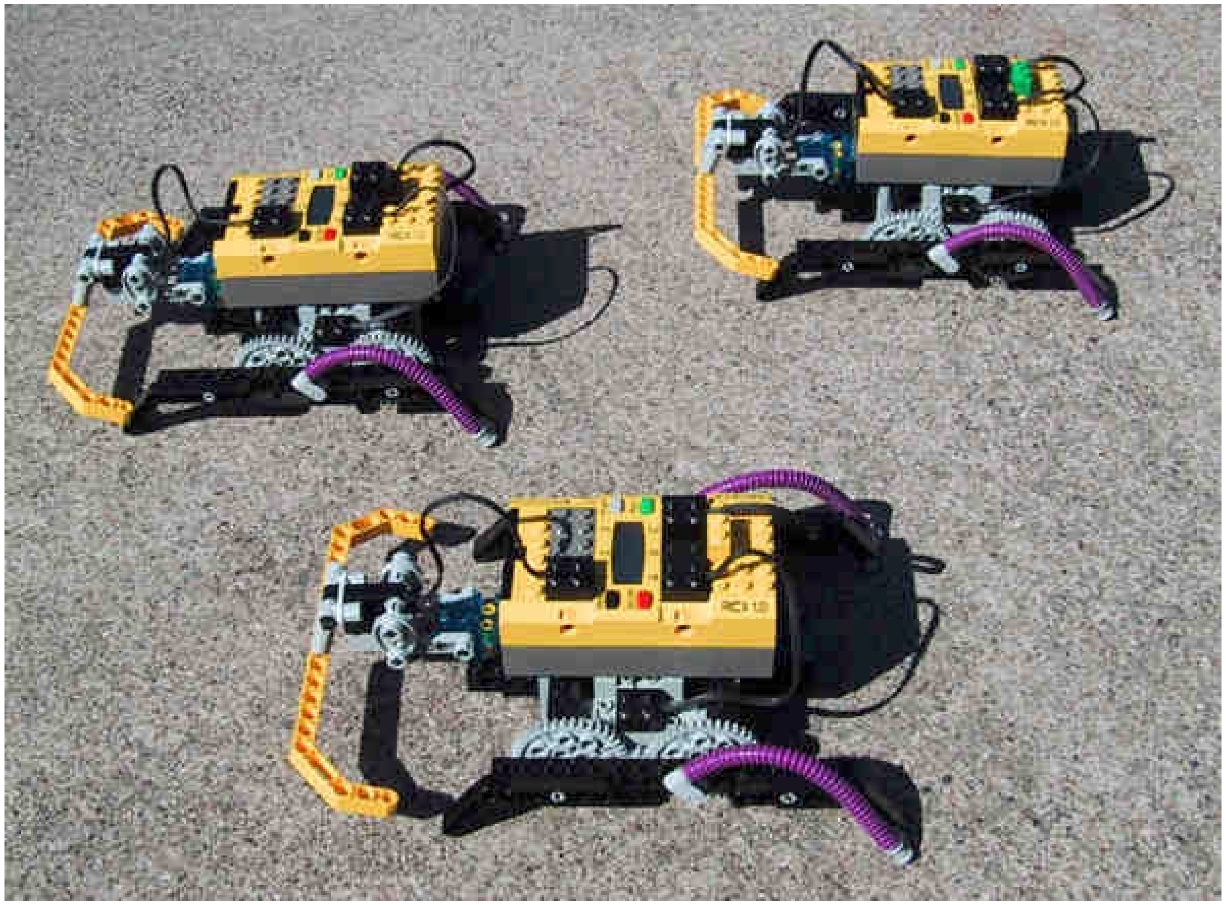
It’s tricky


Mars, July 4, 1997
Lost contact due to embedded software failure

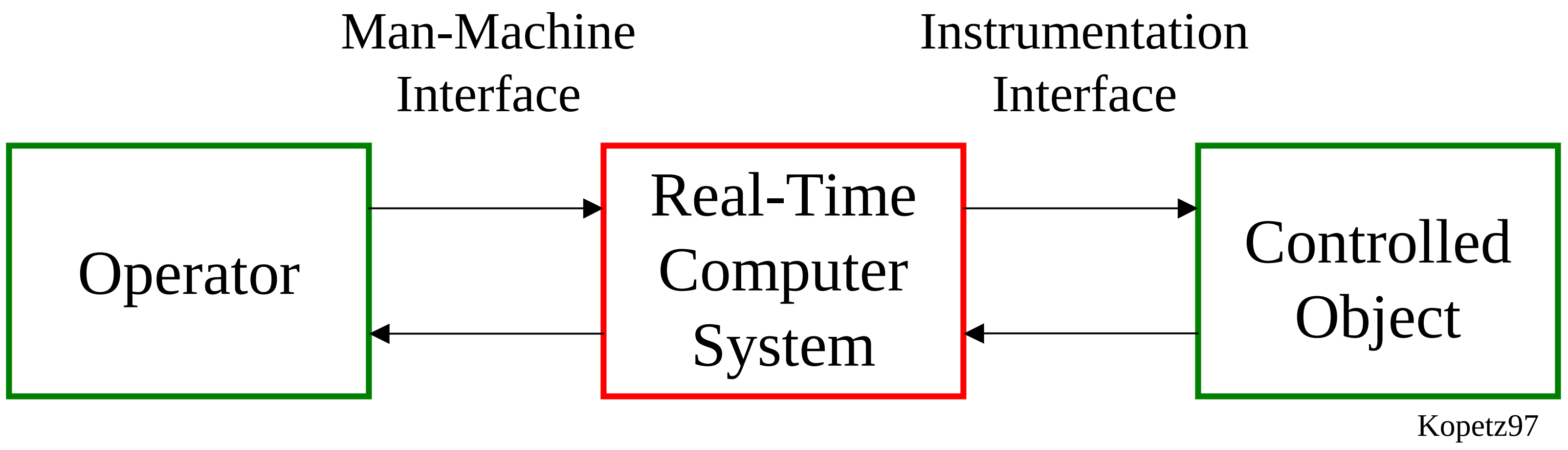
It’s risky


French Guyana, June 4, 1996
$800 million embedded software failure

It’s fun



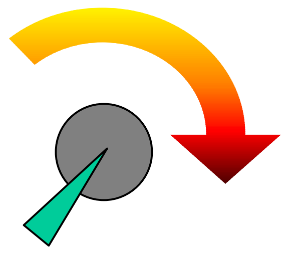
Problem



Methodologies for the implementation of embedded real-time applications

- Methodology: tool-supported, abstract, compositional
- Implementation: compositional, scalable, dependable

Engine Controller

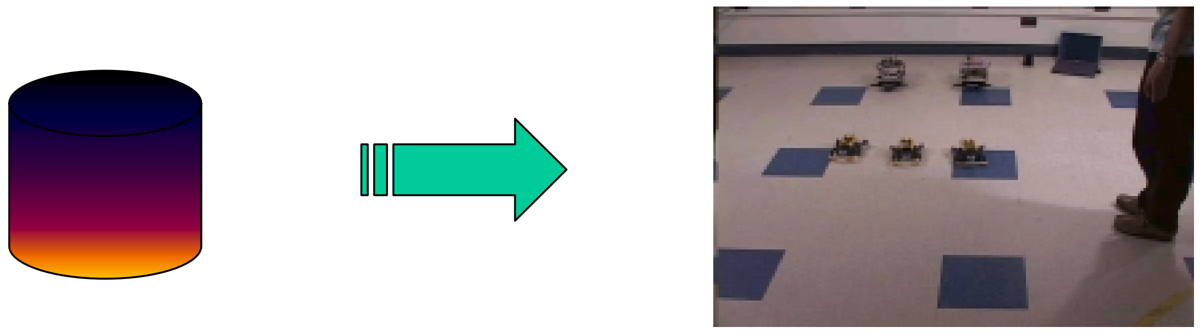


0.1°

@ 6000rpm,
10ms for 360º

- Temporal accuracy of 3µsec
- Up to 100 concurrent software tasks
- Hard real-time: no missed deadlines

Video Streaming



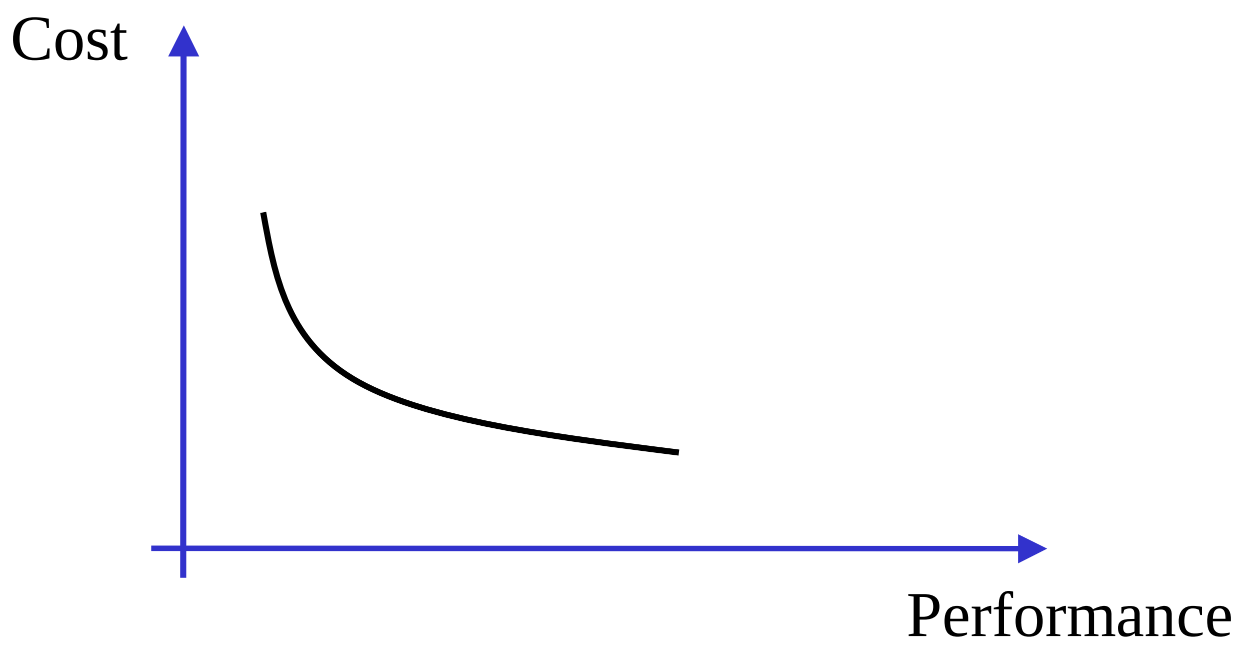
- 25 frames/sec
- Dynamic resource allocation
- Soft real-time: degraded QoS

Real-Time Systems

Characteristics	Hard	Soft
Response time	Hard-required	Soft-desired
Peak-load performance	Predictable	Degraded
Control of pace	Environment	Computer
Redundancy	Active	Checkpoint
Error detection	Autonomous	User assisted

Kopetz97

Microcontroller Market

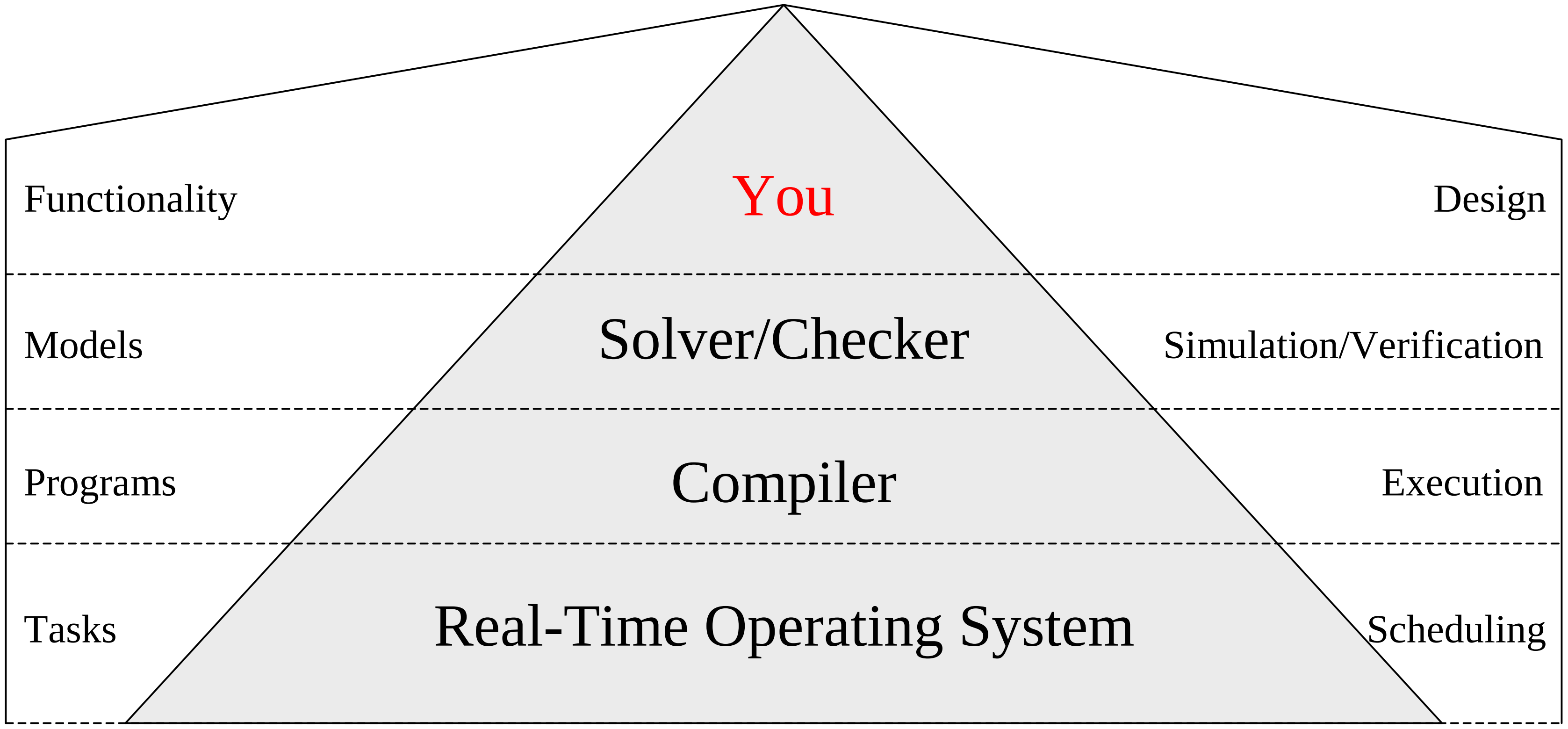


Mechatronics

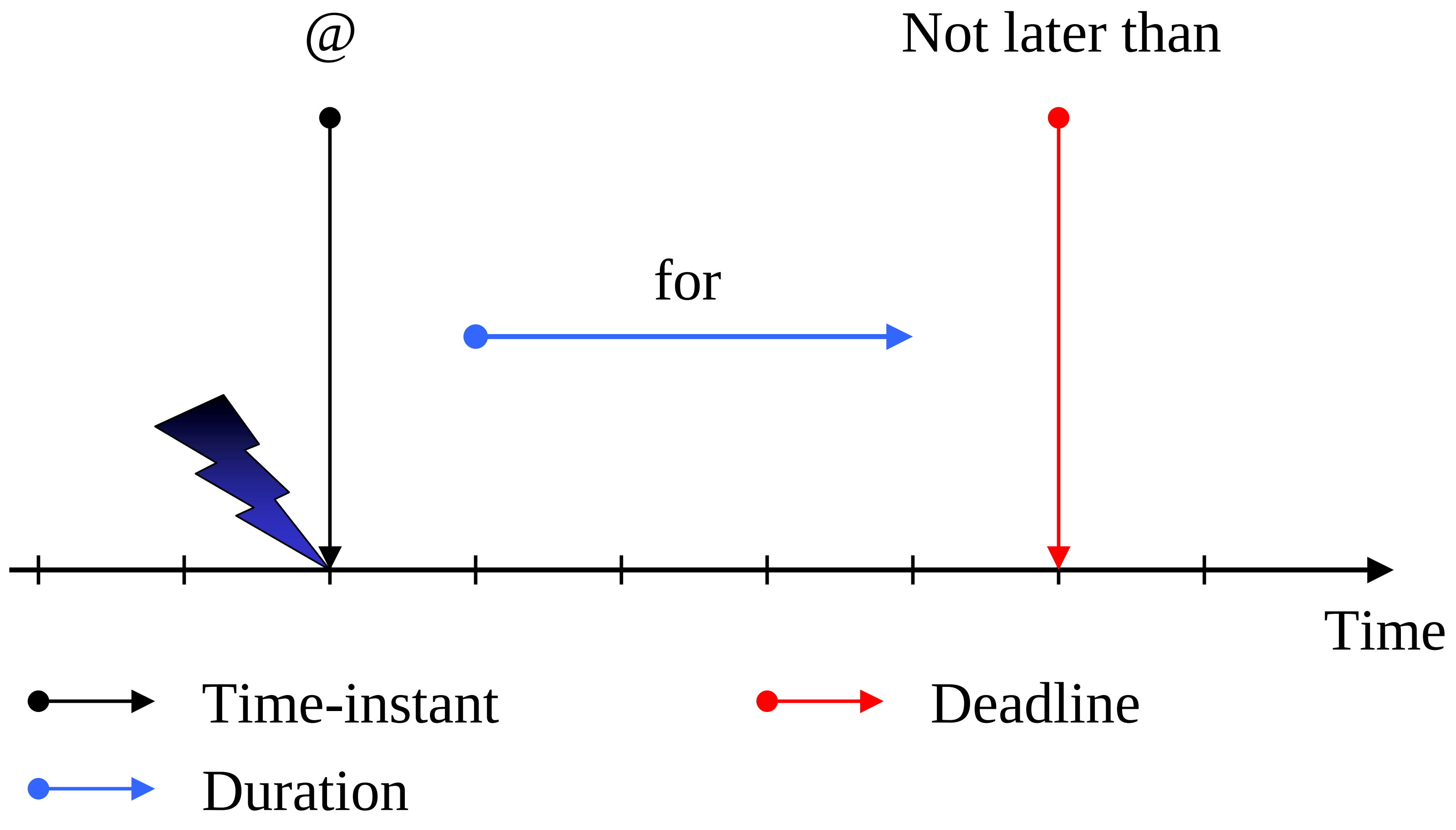
Fly-by-wire

Drive-by-wire

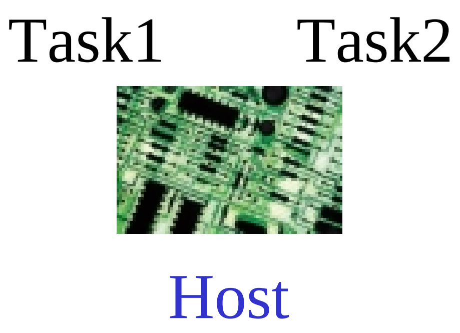
Embedded Software Engineering

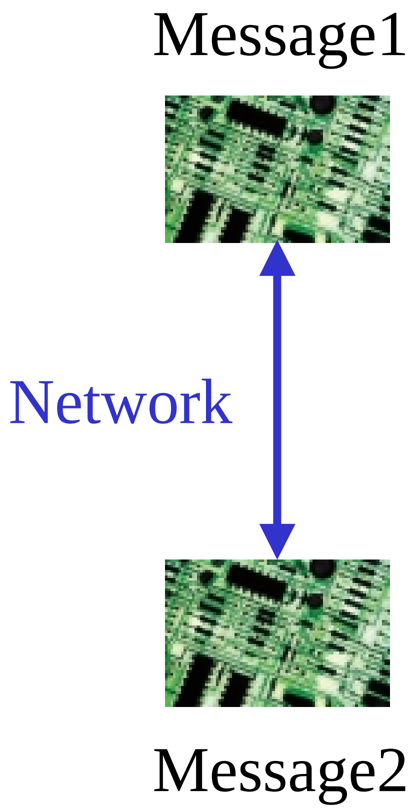


Real-Time



Concurrency

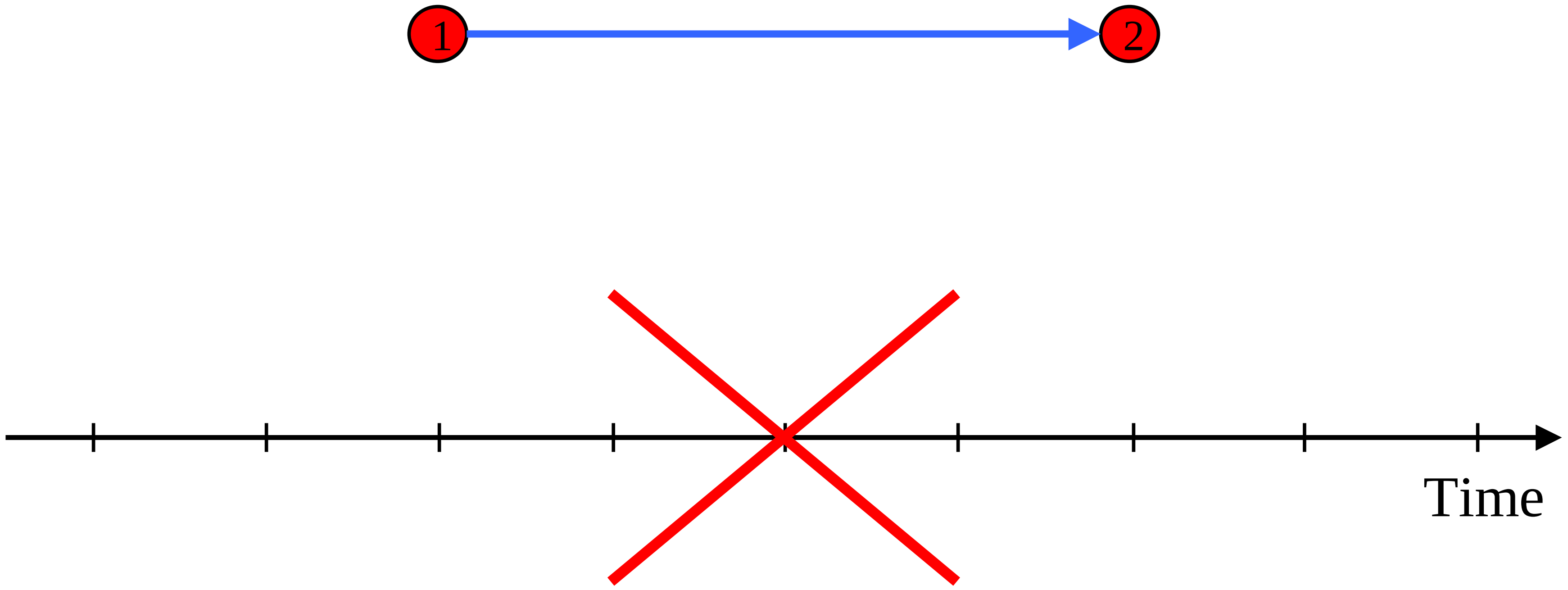




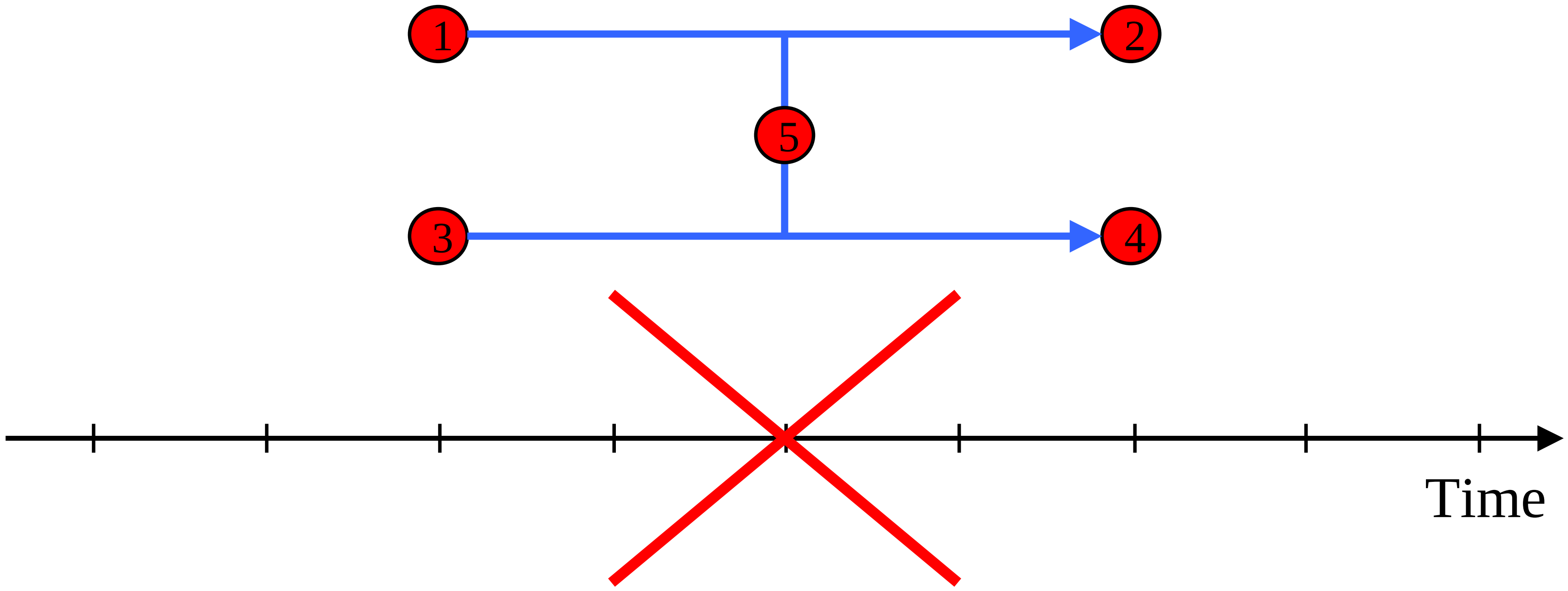
In addition:

- Other resource constraints
- Time constraints

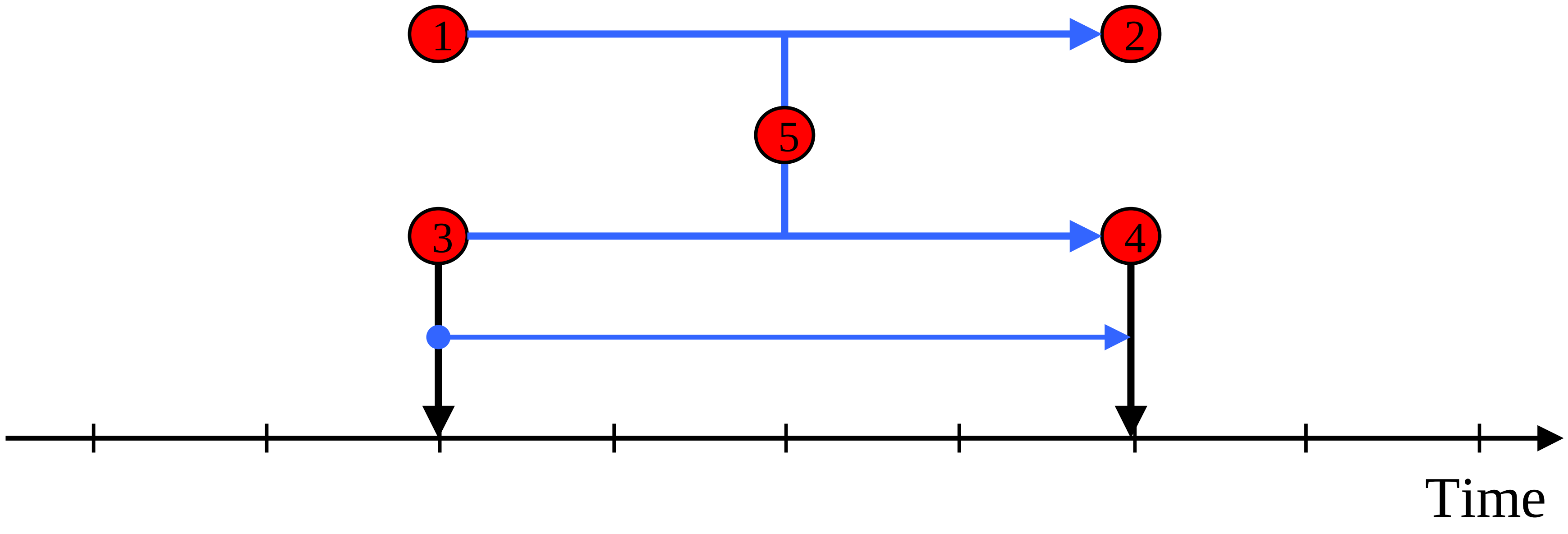
Sequential Programming



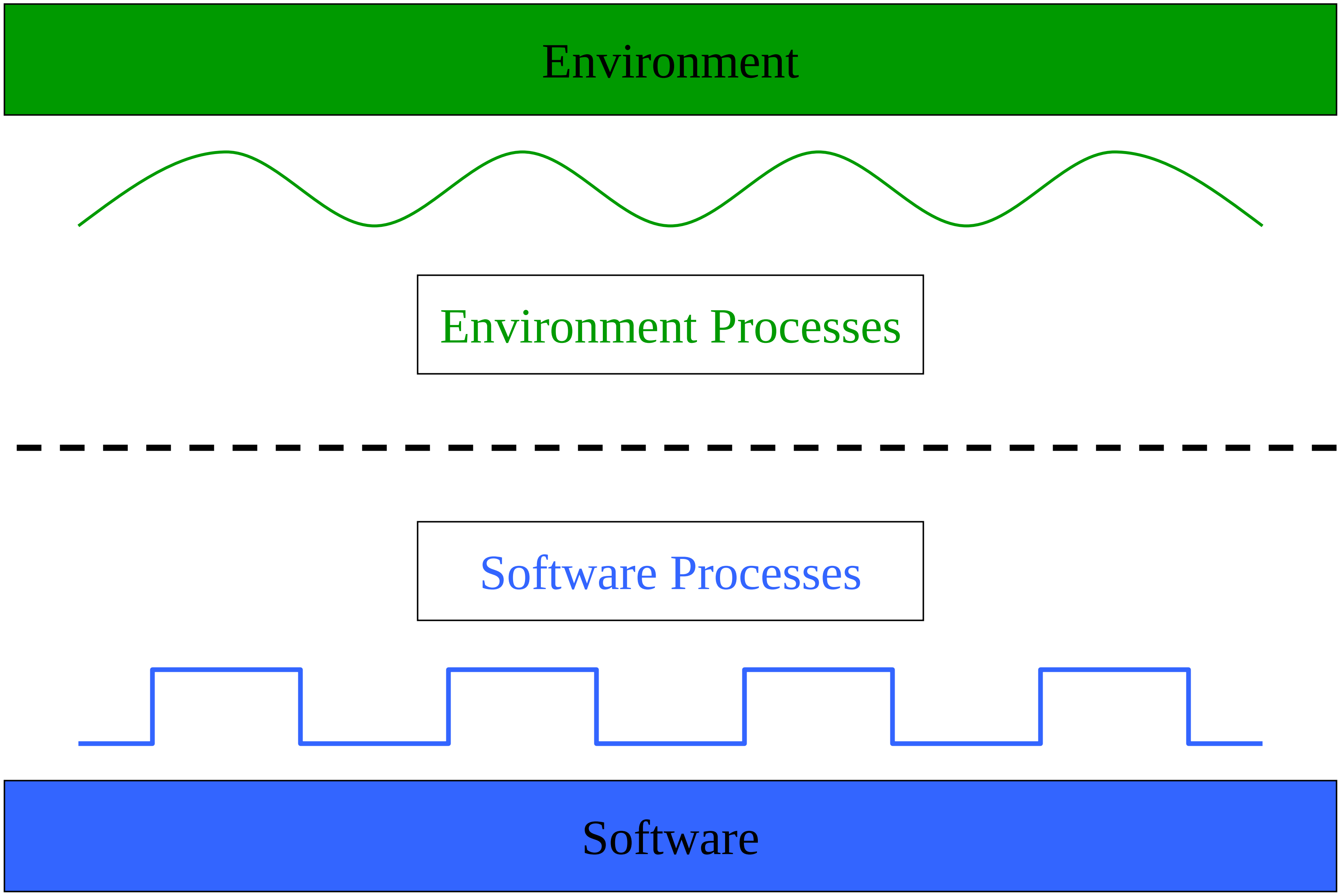
Multiprogramming



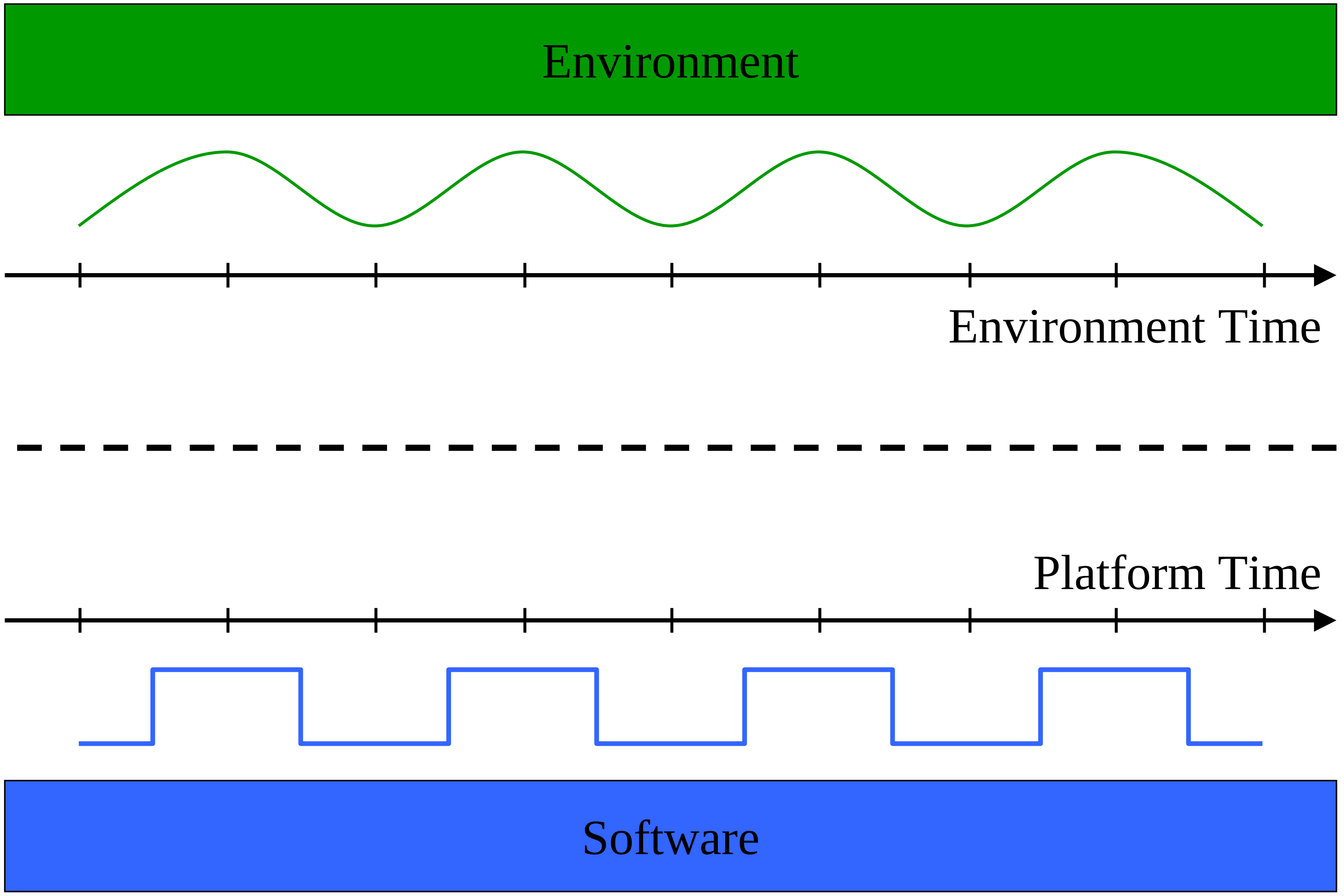
Real-Time Programming



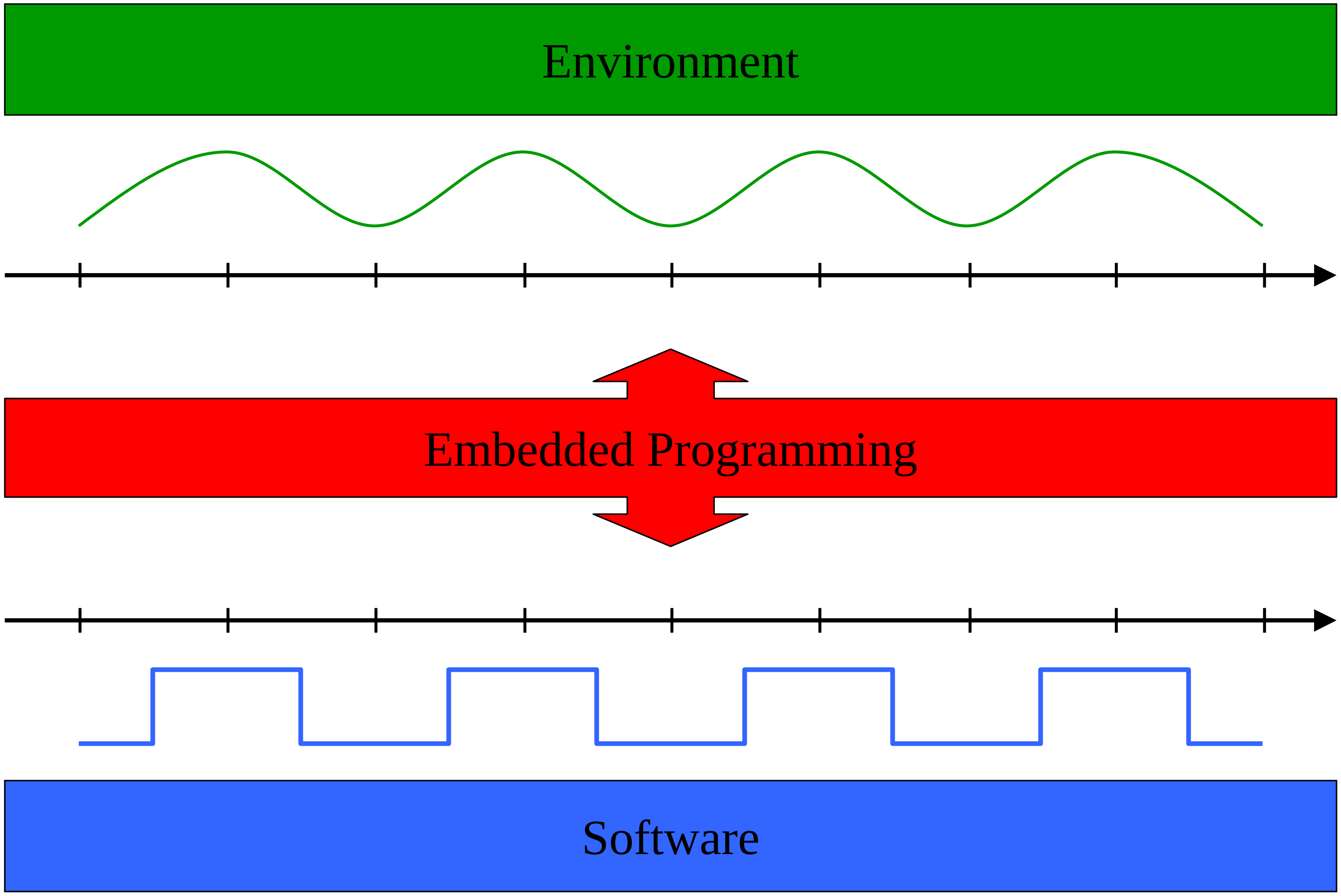
Embedded Software



Environment vs. Platform Time



The Art of Embedded Programming

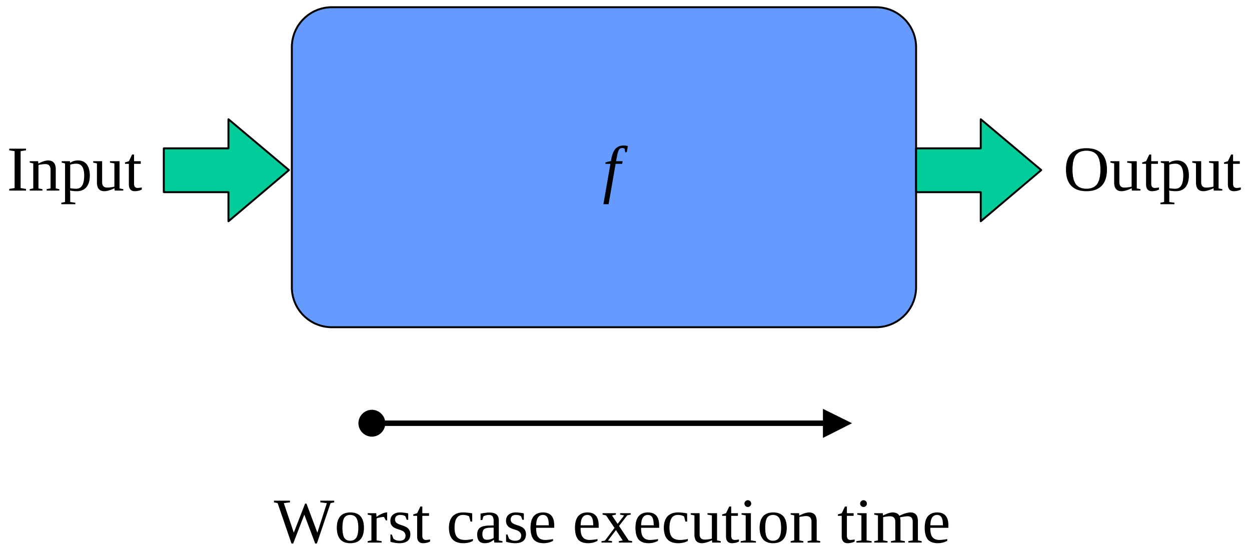


Embedded Programming

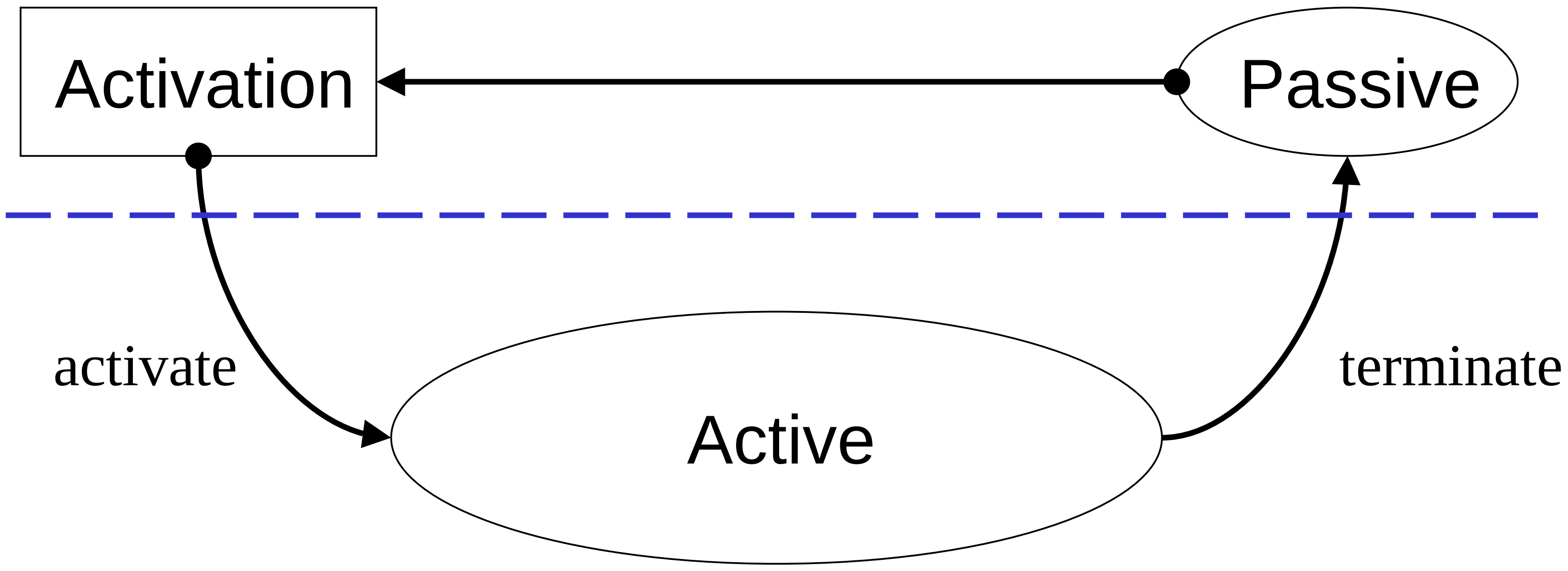
…requires the integration of:

1. Real-time operating system concepts
2. Embedded programming languages
3. Embedded compilers
4. SE, modeling, and simulation techniques
5. Formal methods

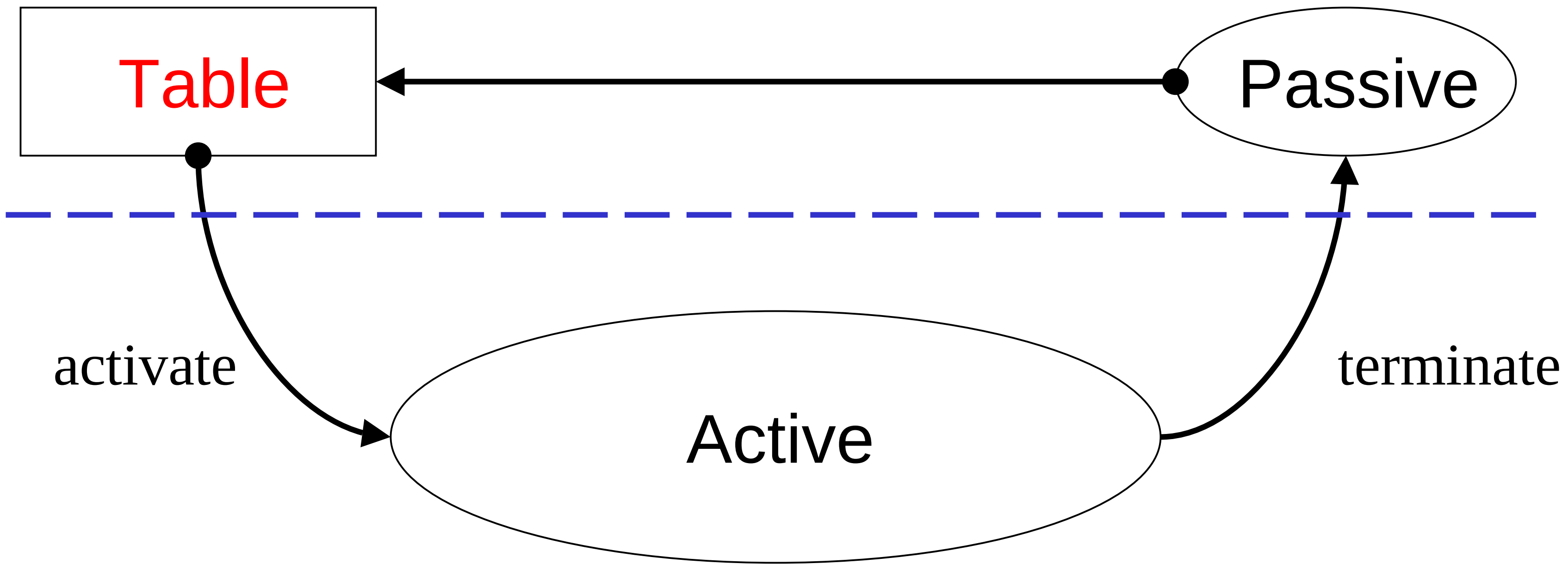
Real-Time Task



Real-Time Scheduling

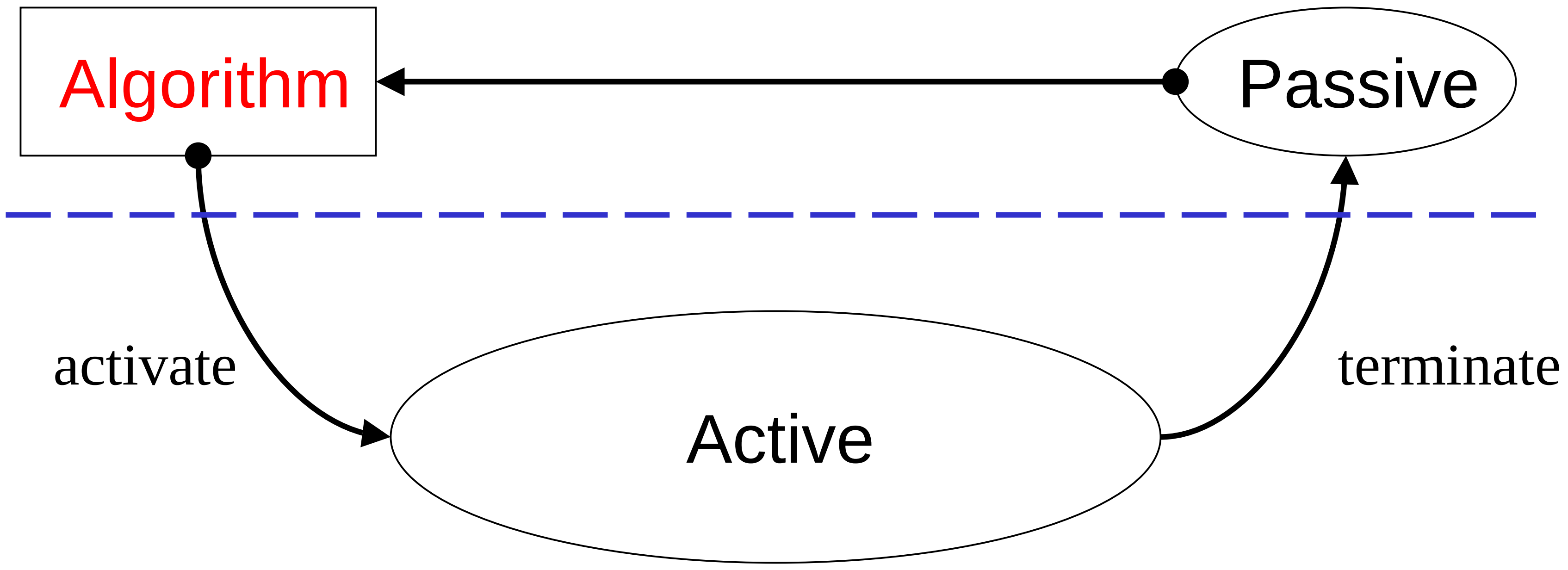


Off-Line Scheduling



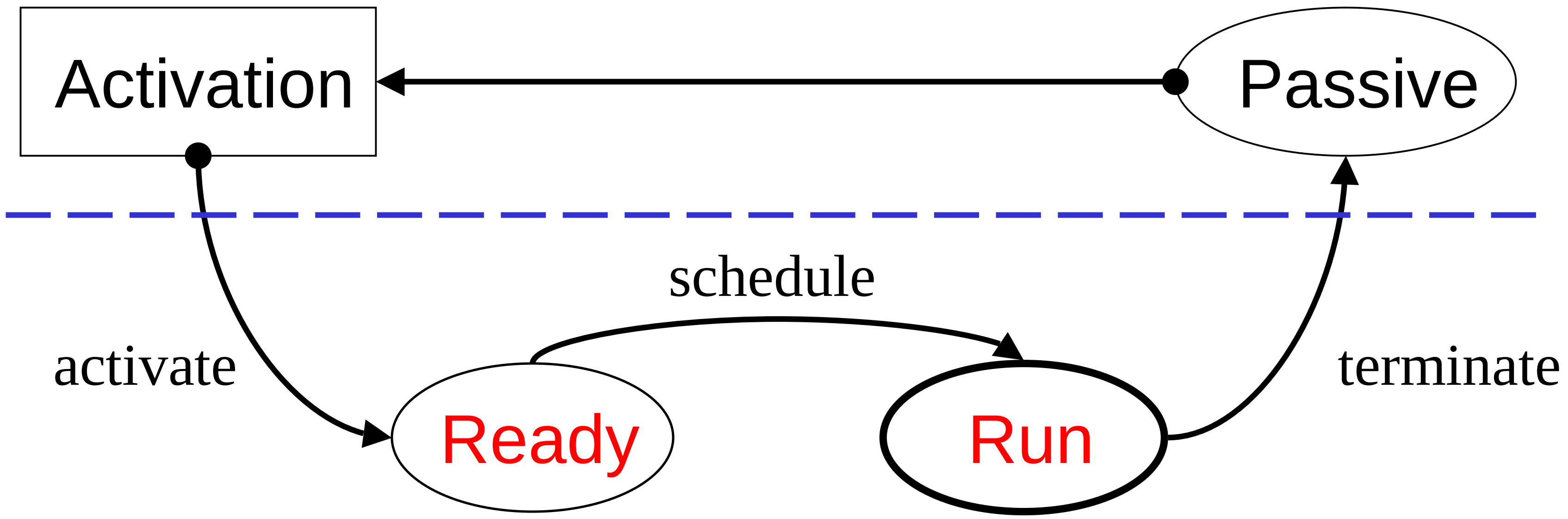
Static System

On-Line Scheduling

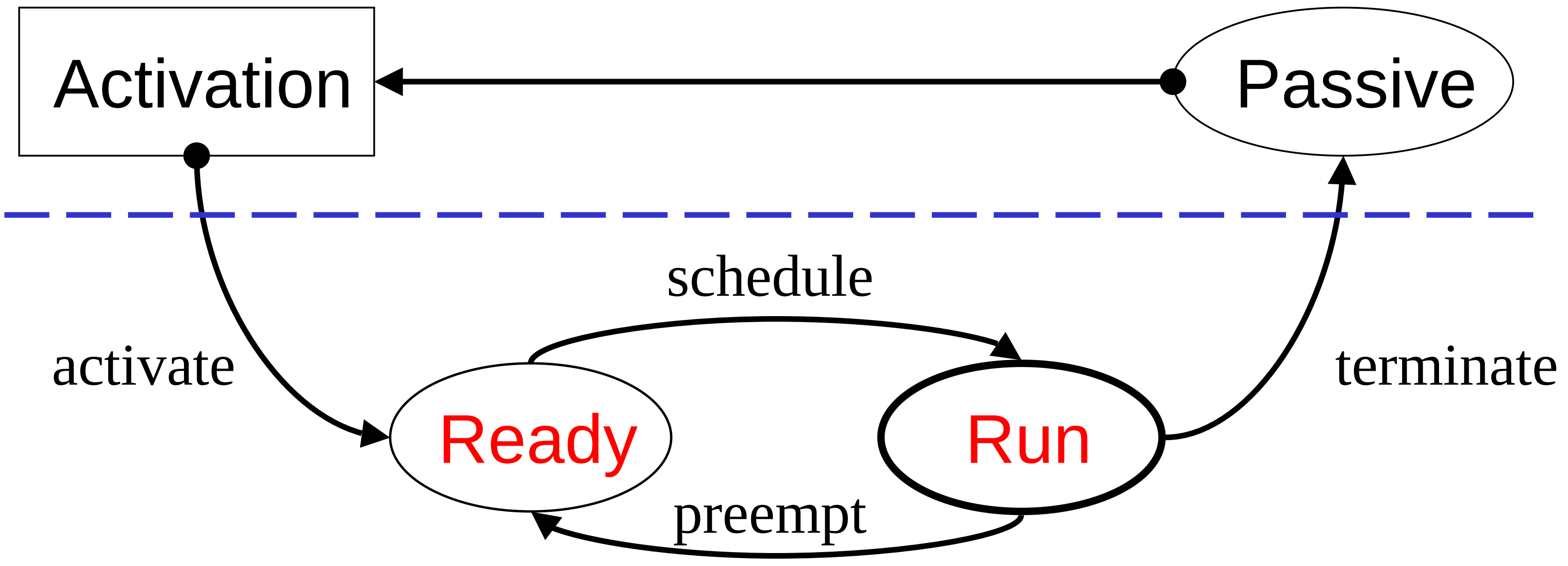


Dynamic System

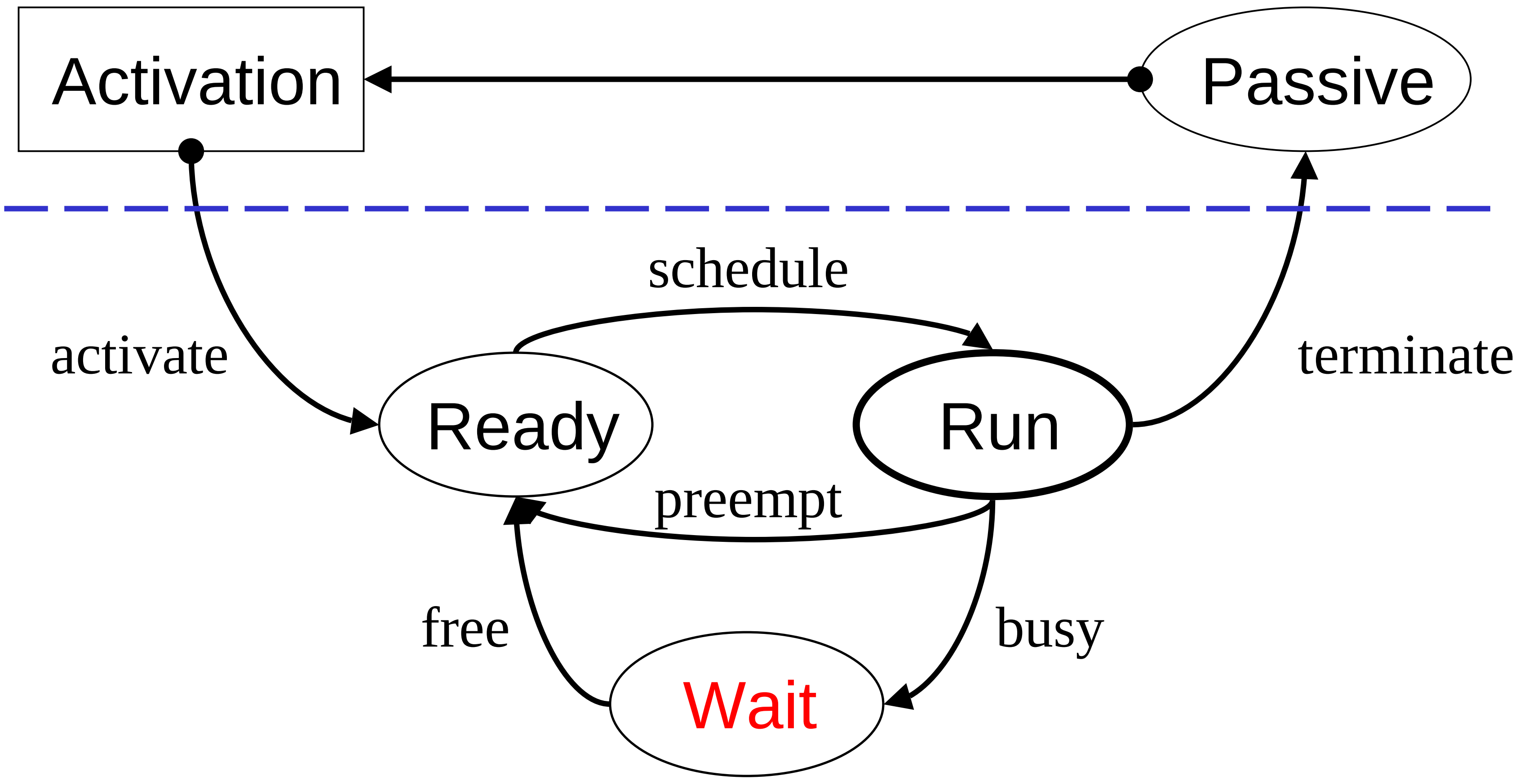
Non-Preemptive Scheduling



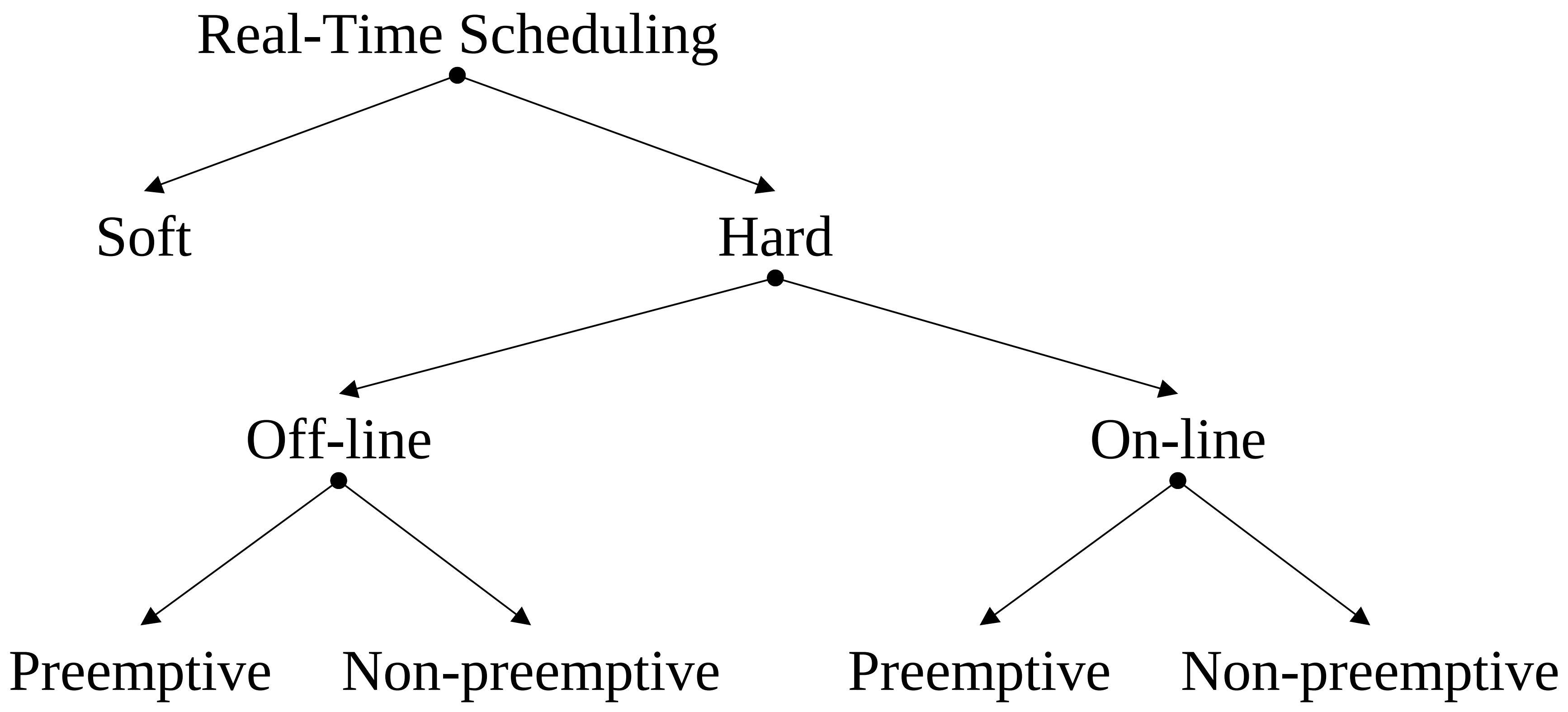
Preemptive Scheduling



Shared Resources



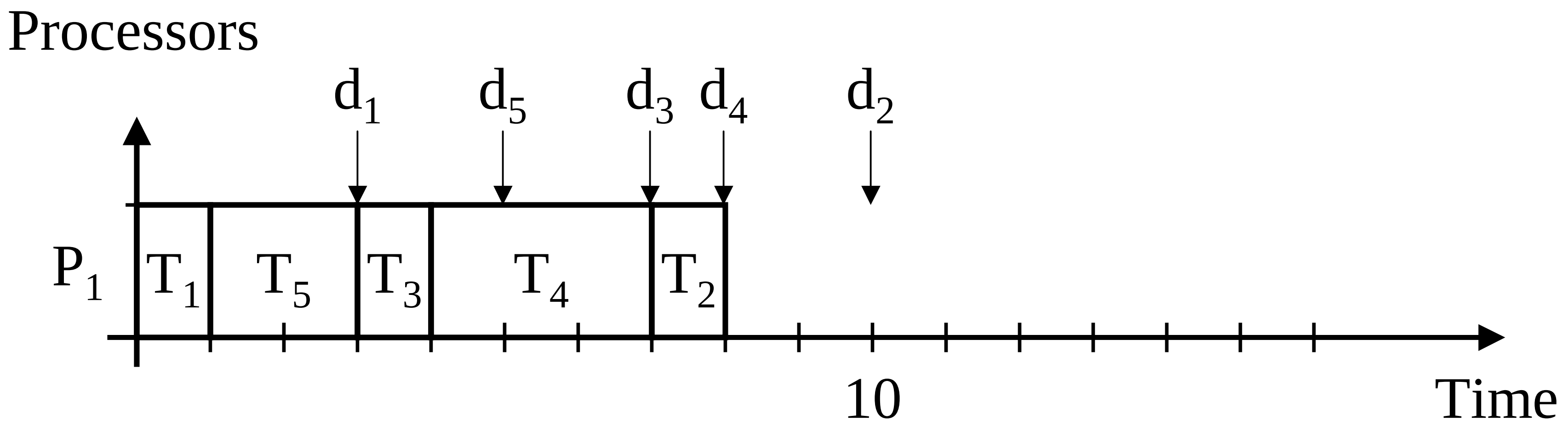
Scheduling Problem



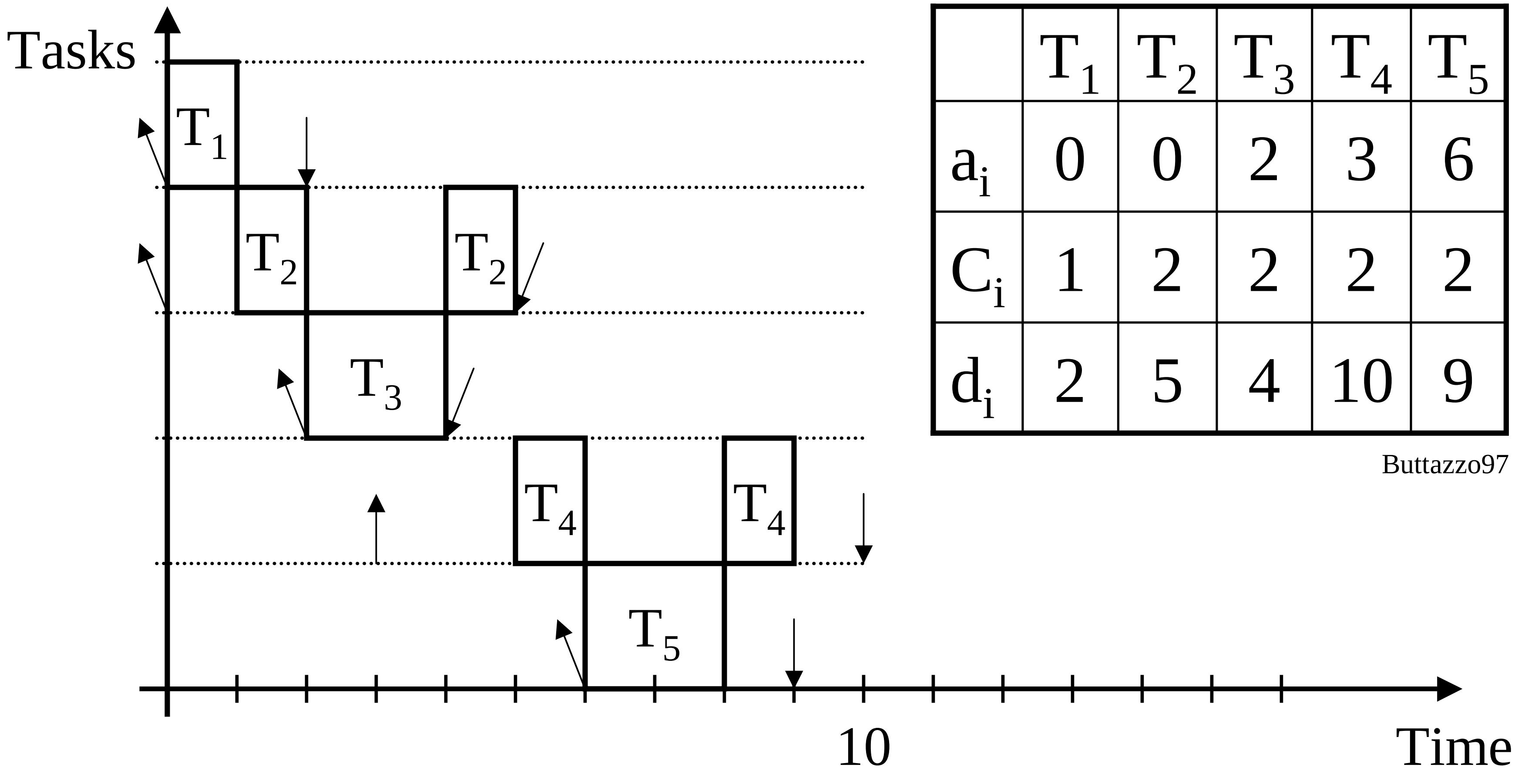
Earliest Due Date

	T_1	T_2	T_3	T_4	T_5
C_i	1	1	1	3	2
d_i	3	10	7	8	5

Buttazzo97



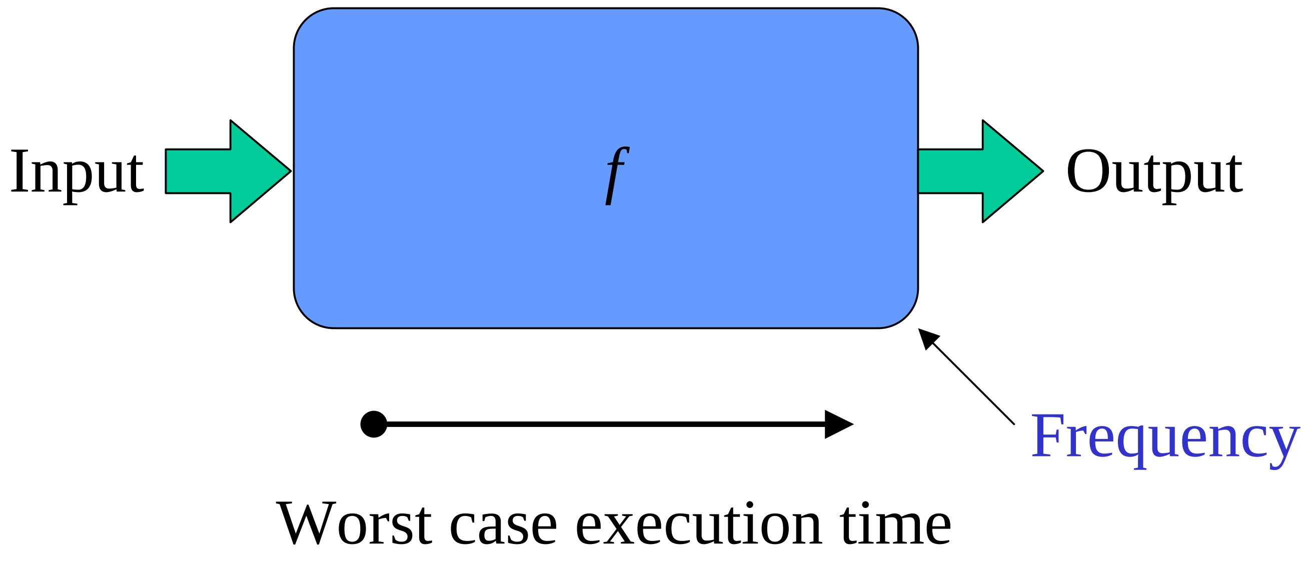
Earliest Deadline First



	T_1	T_2	T_3	T_4	T_5
a_i	0	0	2	3	6
C_i	1	2	2	2	2
d_i	2	5	4	10	9

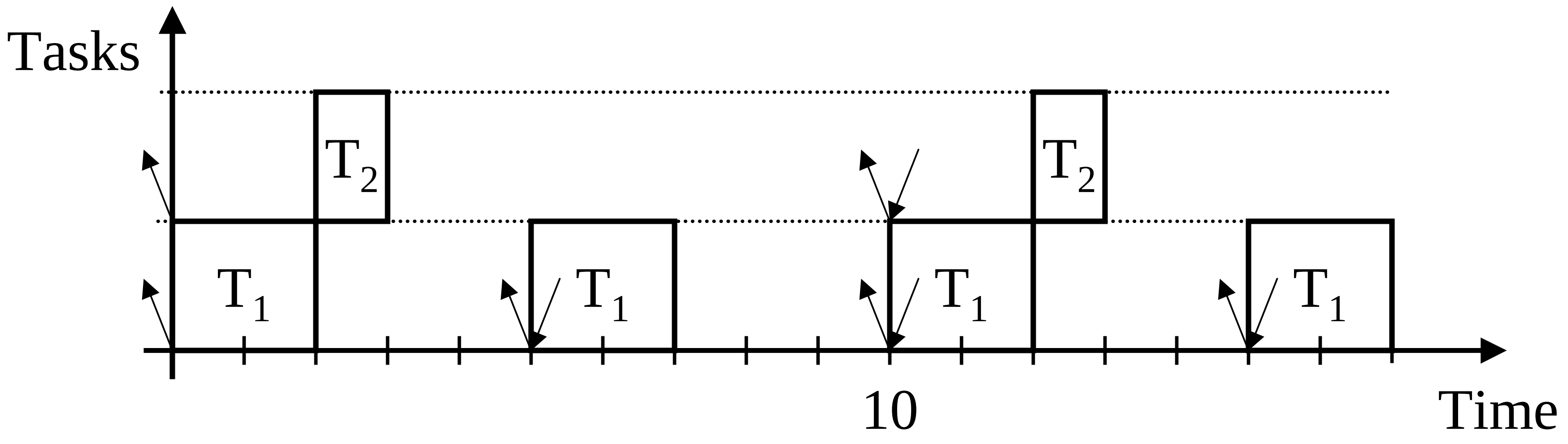
Buttazzo97

Real-Time Periodic Task

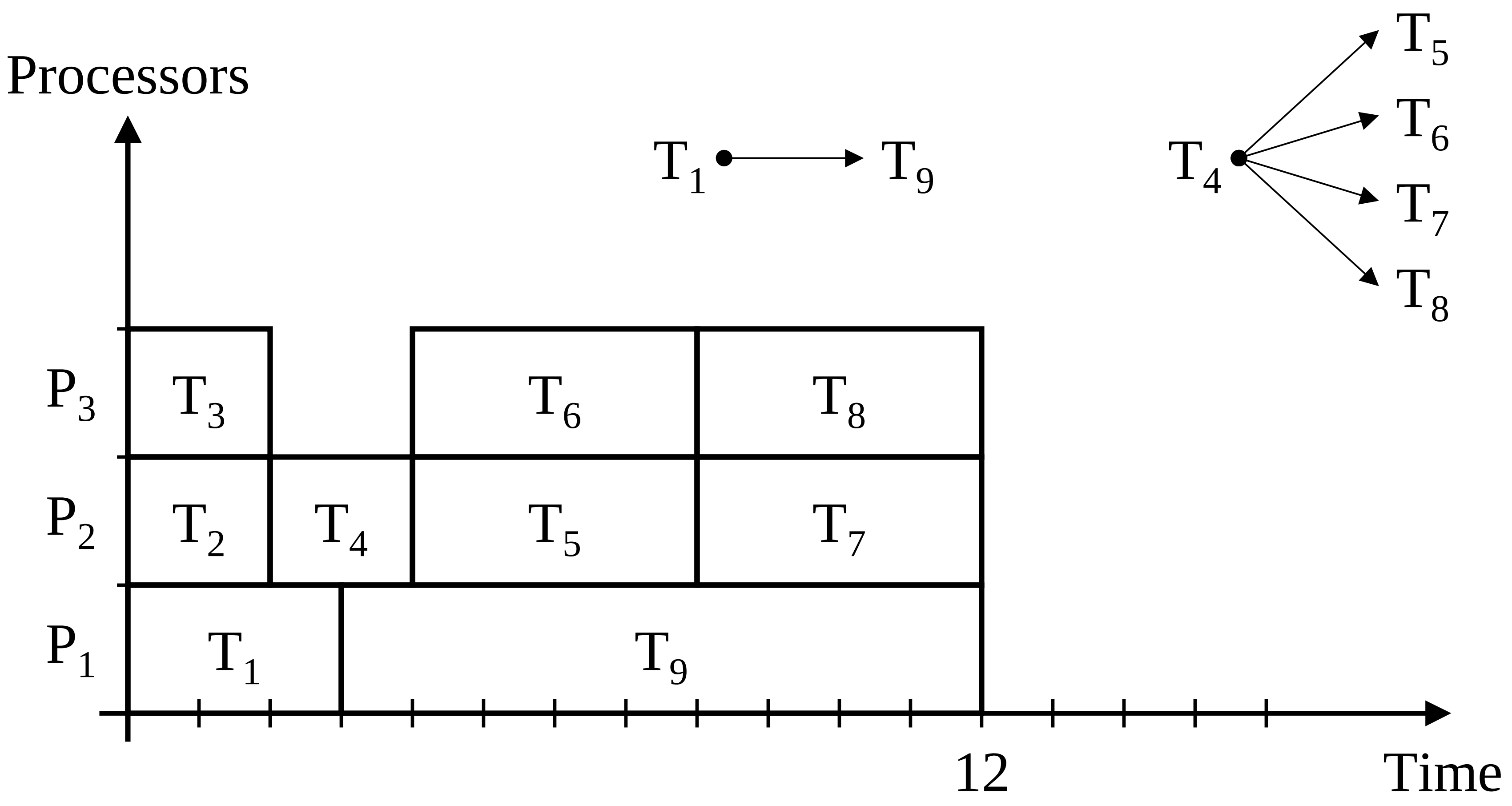


Rate Monotonic Analysis

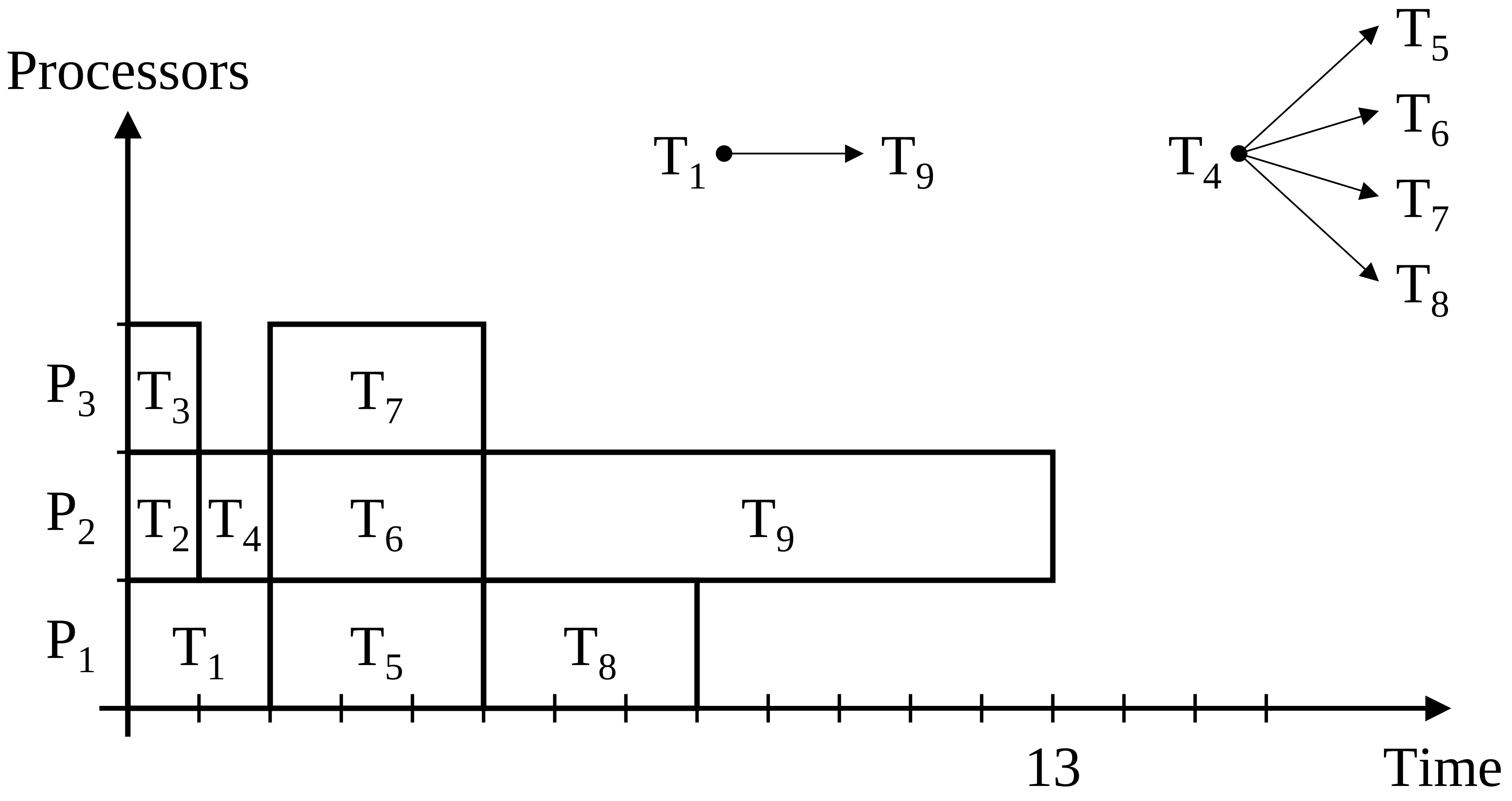
	T_1	T_2
C_i	2	1
p_i	5	10



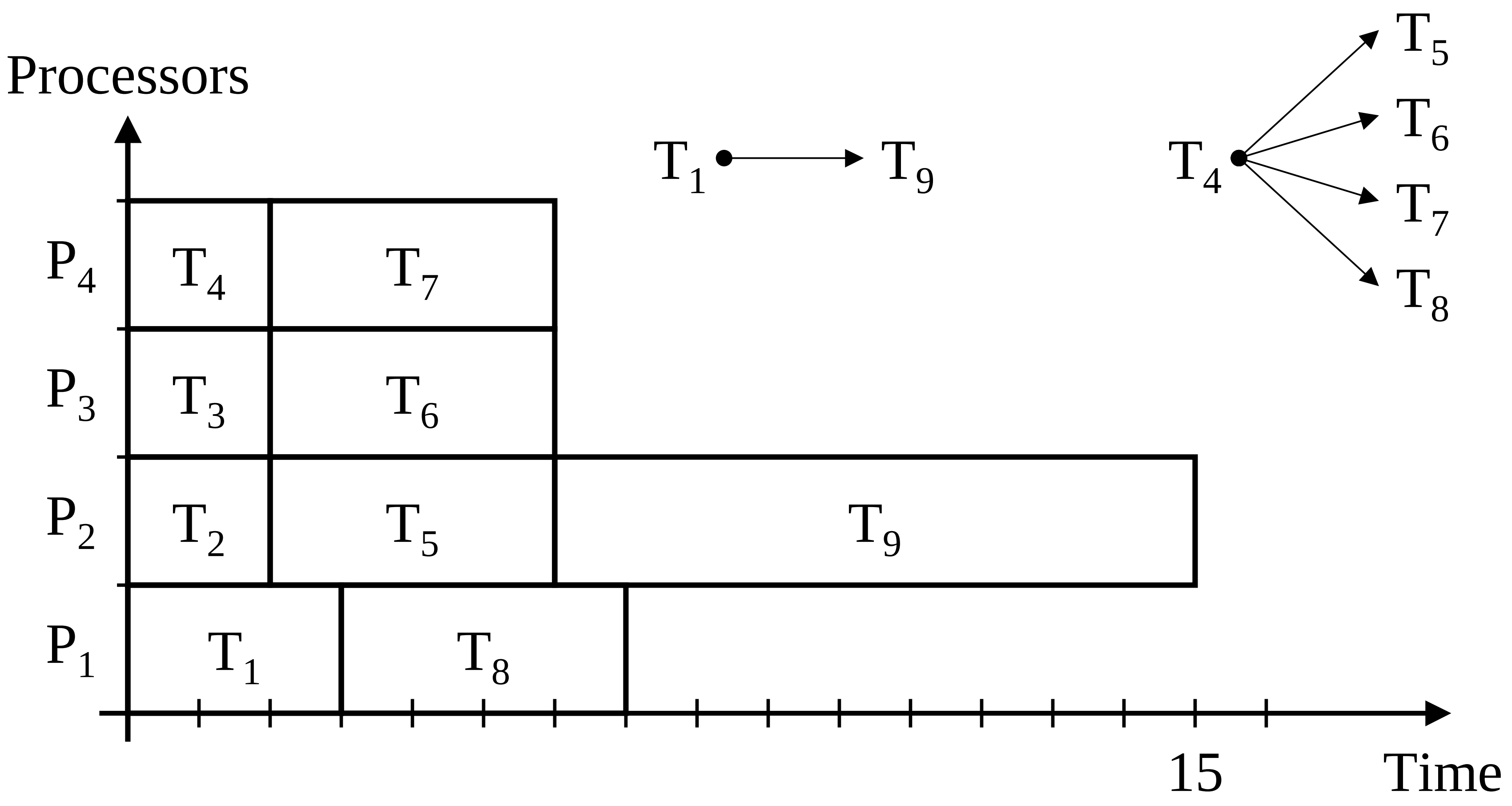
Scheduling Anomalies



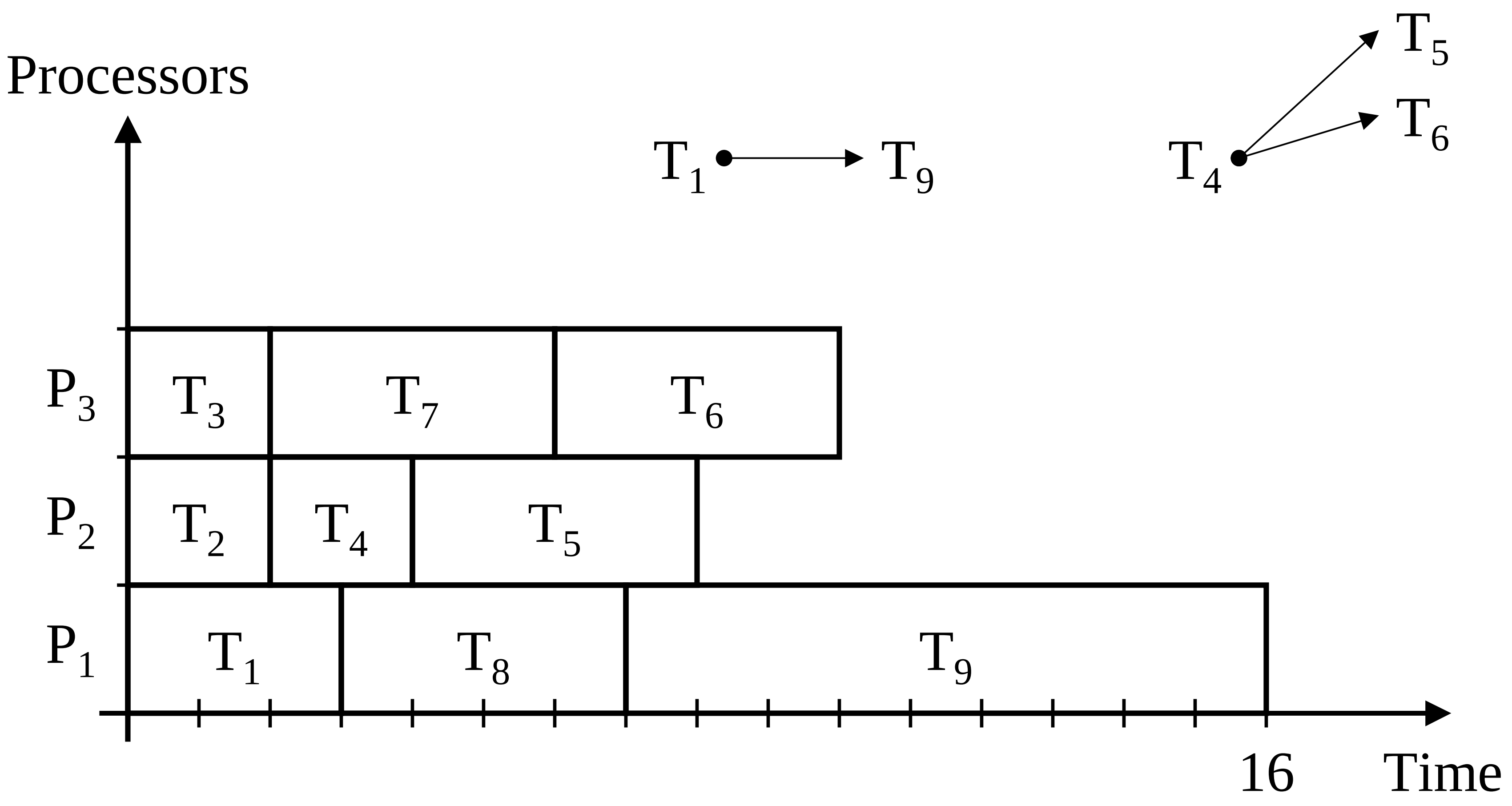
Shorter Computation Times



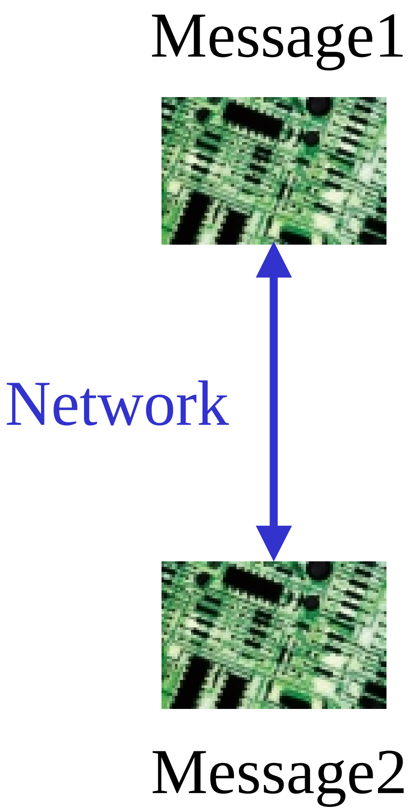
More Processors



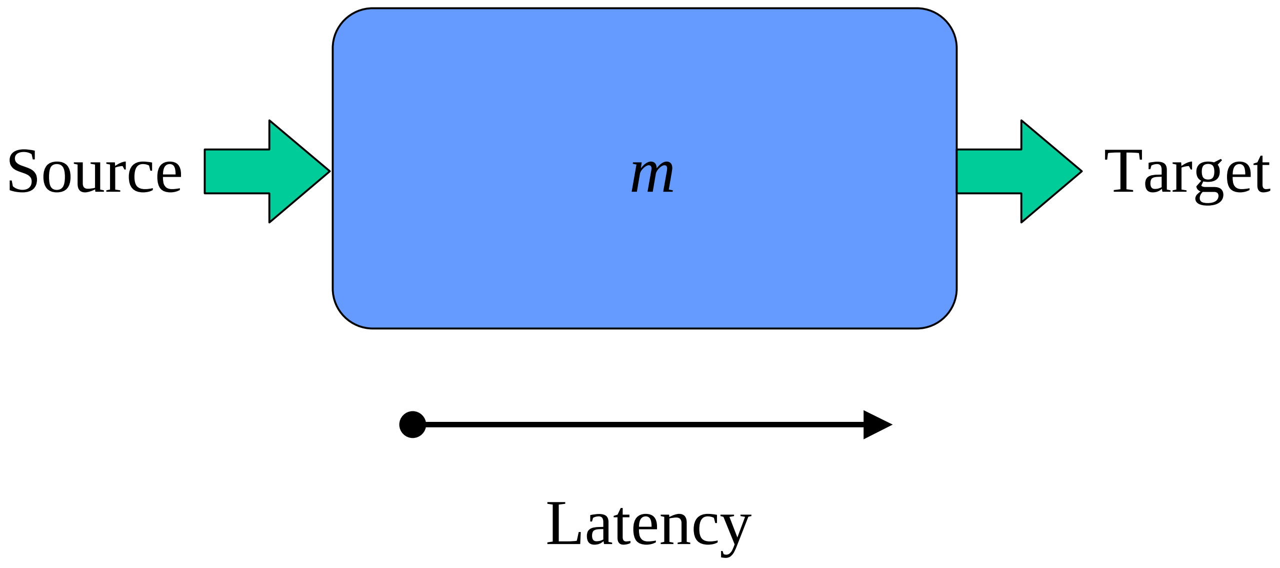
Weaker Precedence



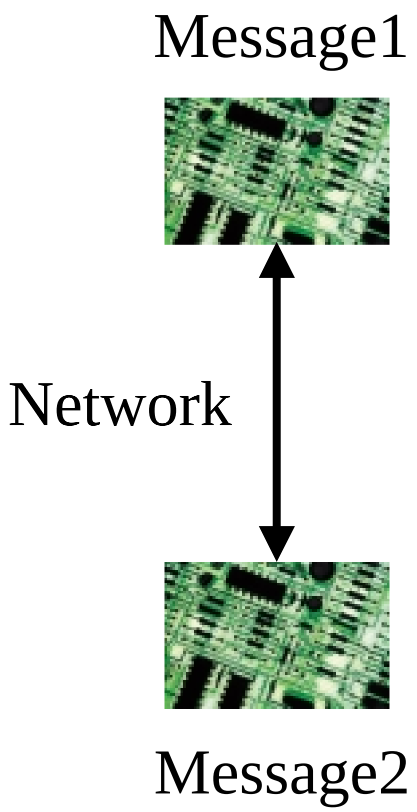
Real-Time Communication



Real-Time Message

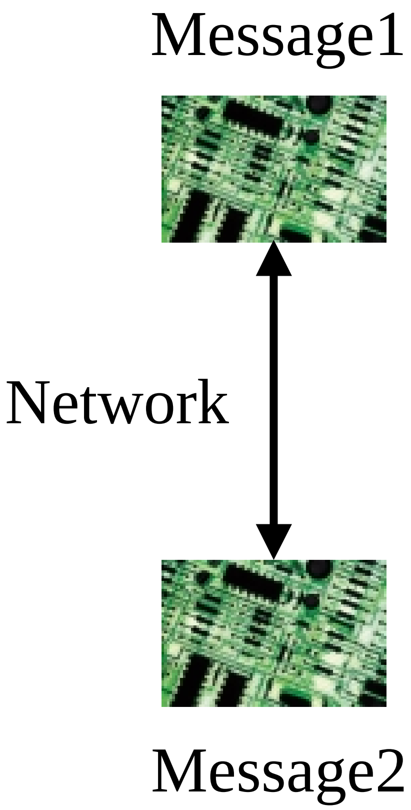


Explicit Flow Control



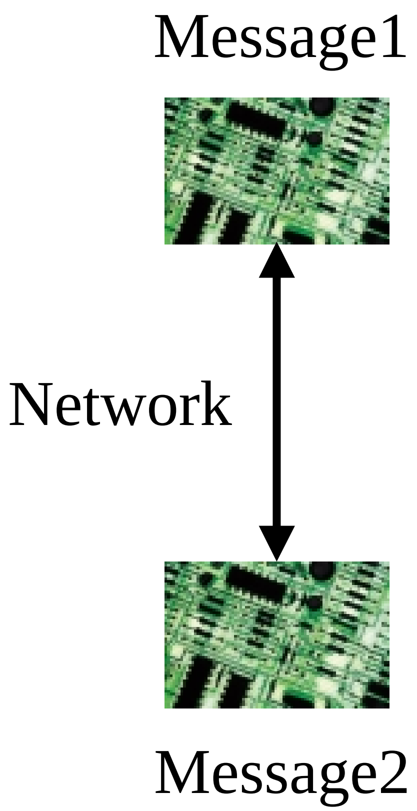
- Send time not known a priori
- Sender can detect errors

Implicit Flow Control



- Send time is known a priori
- Receiver can detect errors

Explicit Flow Control: Priority

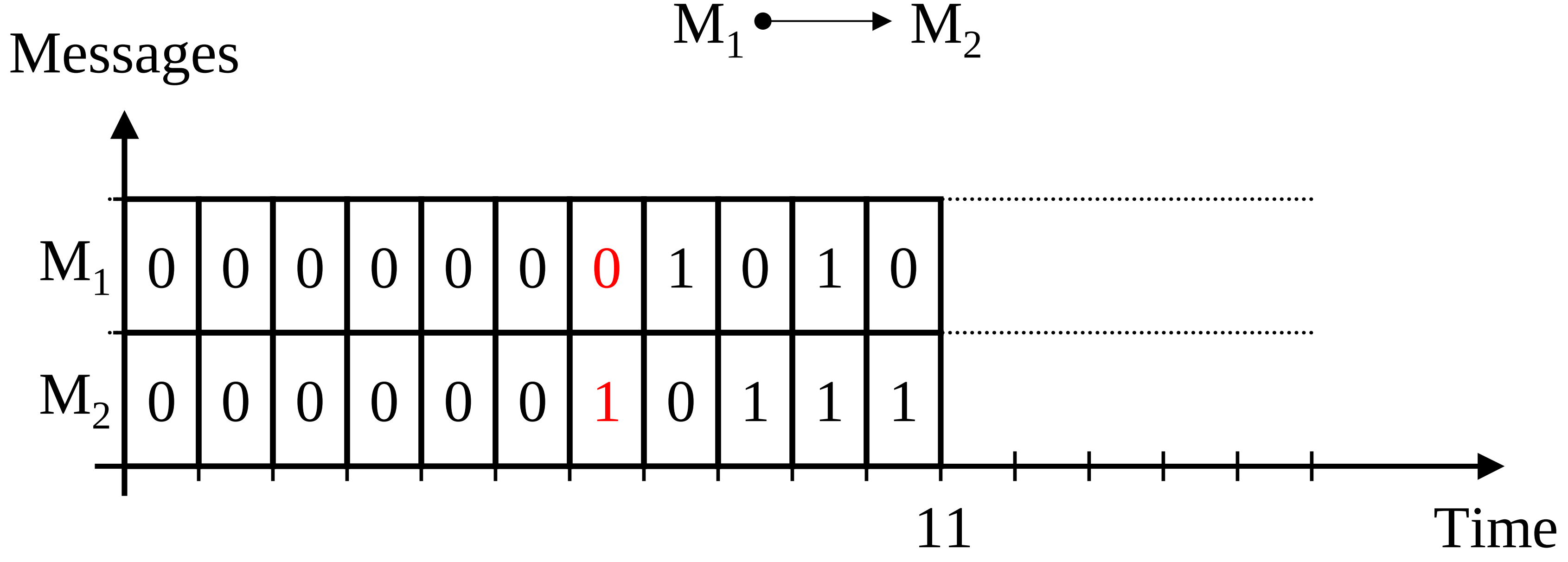


Medium-Access Protocols:

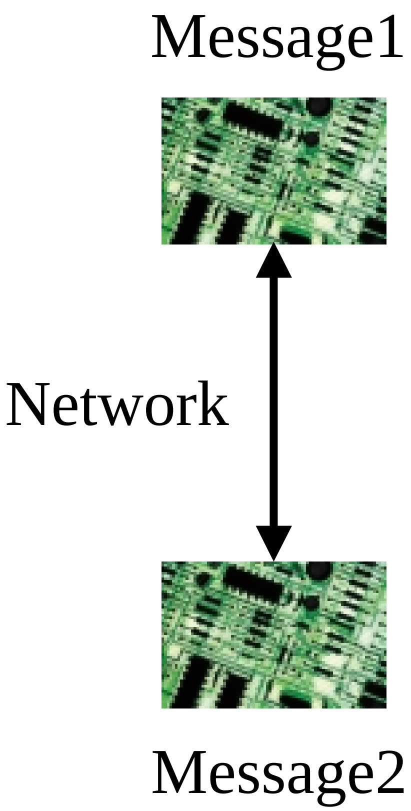
- CSMA/CD - LON, Echelon 1990
- CSMA/CA - CAN, Bosch 1990
- FTDMA - Byteflight, BMW 2000
- TDMA - TTP, Kopetz 1993

Control Area Network

$M_1 \longrightarrow M_2$



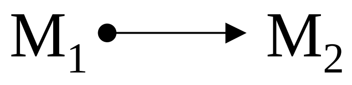
Implicit Flow Control: Time

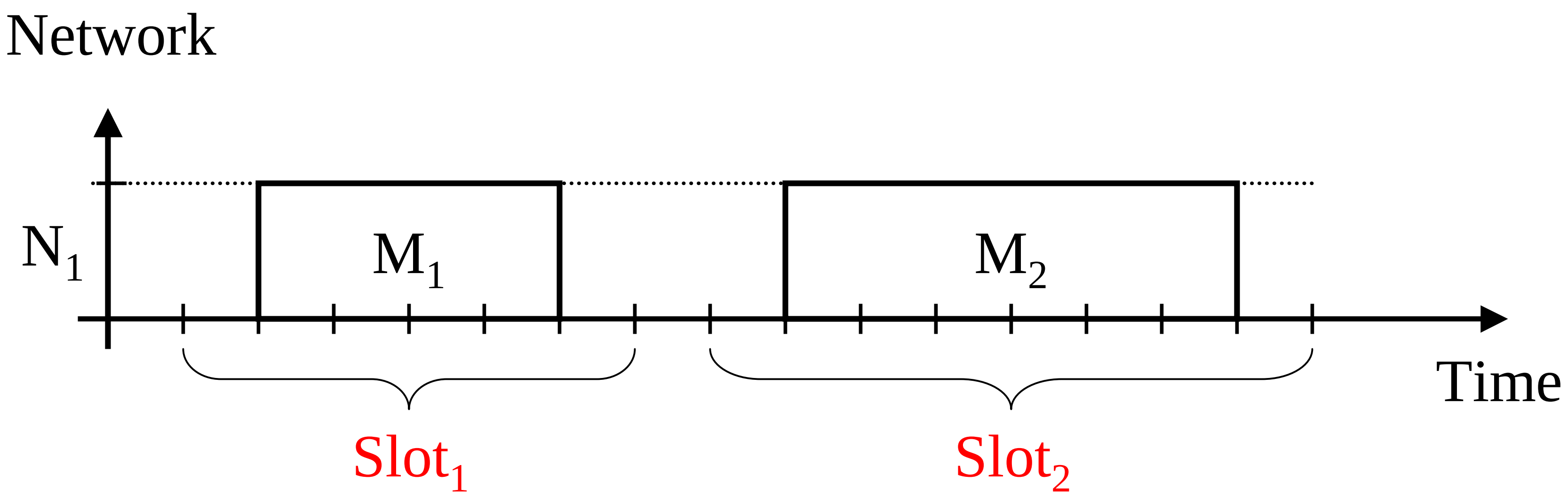


Medium-Access Protocols:

- FTDMA - Byteflight, BMW 2000
- TDMA - TTP, Kopetz 1993

Time-Triggered Protocol





Literature

- RT scheduling:
  - Hard Real-Time Computing Systems: Predictable Scheduling Algorithms and Applications. G. Buttazzo. Kluwer, 1997.
- RT communication:
  - Real-Time Systems – Design Principles for Distributed Embedded Applications. H. Kopetz. Kluwer, 1997.
  - Byteflight, CAN papers.

Embedded Programming

…requires the integration of:

1. Real-time operating system concepts
2. Embedded programming languages
3. Embedded compilers
4. SE, modeling, and simulation techniques
5. Formal methods

Concurrency

Parallel Composition

Task1 $\|$ Task2

Control

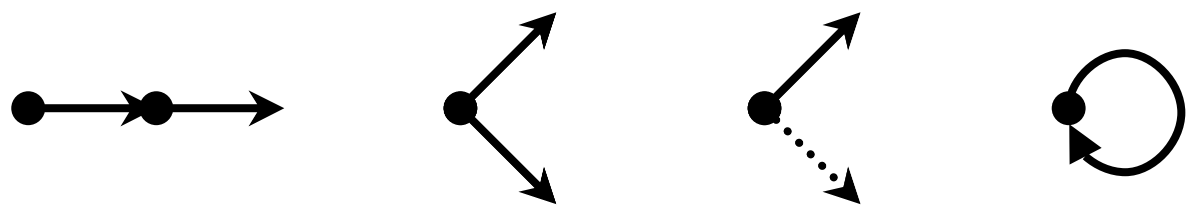
I/O Decomposition

Task1 $\longleftrightarrow$ Task2

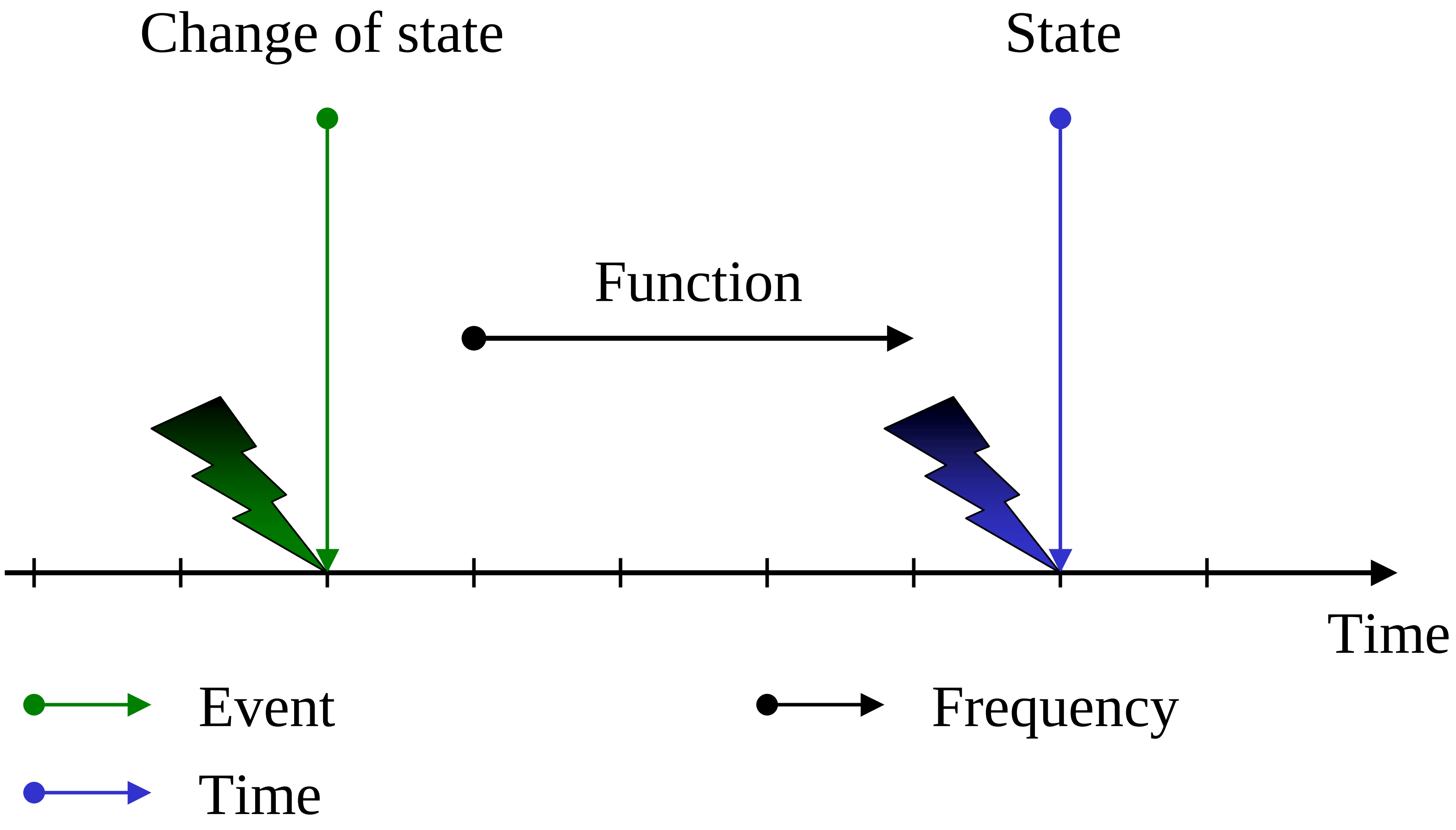
Data

Control Operators

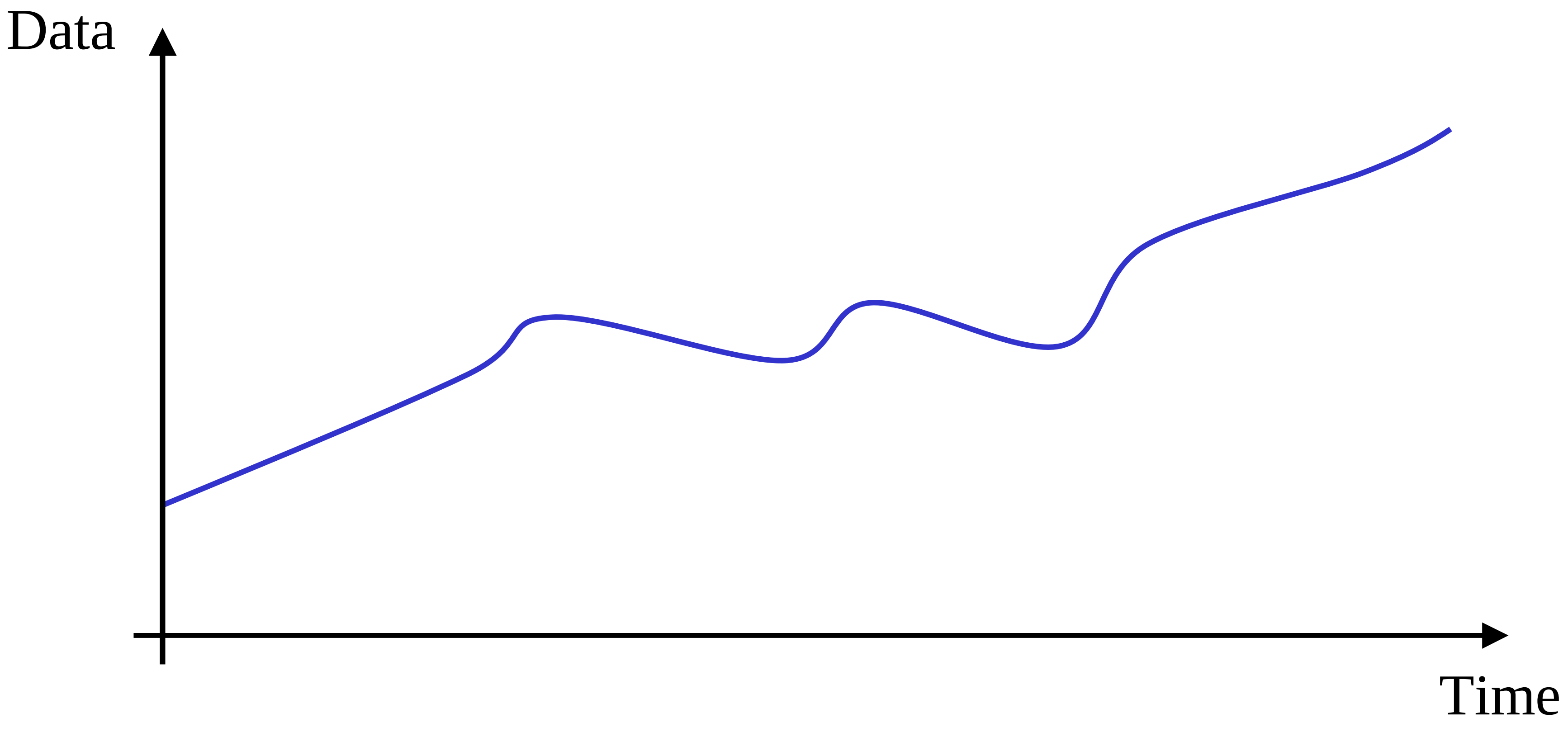
Sequential Parallel Choice Loop



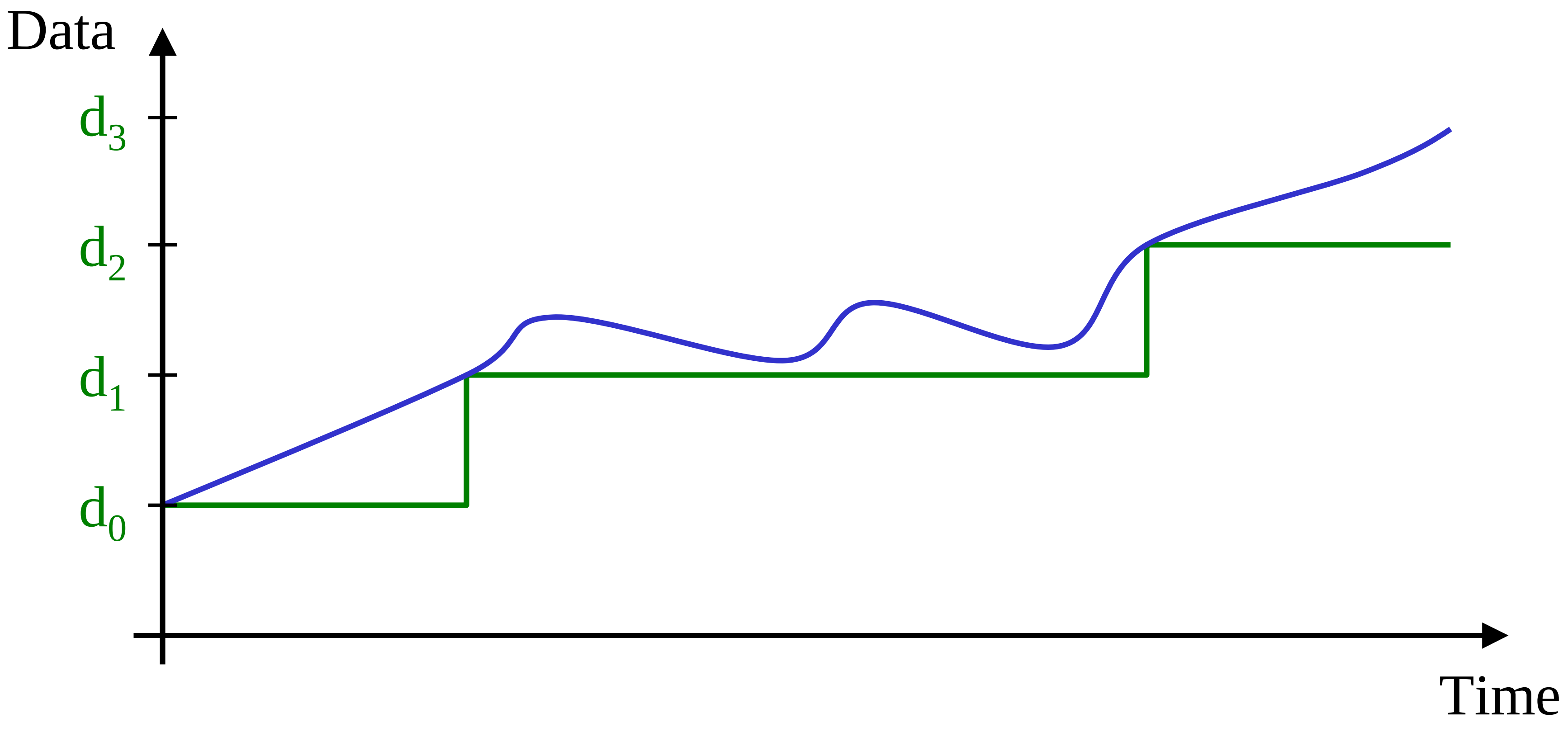
Real-Time



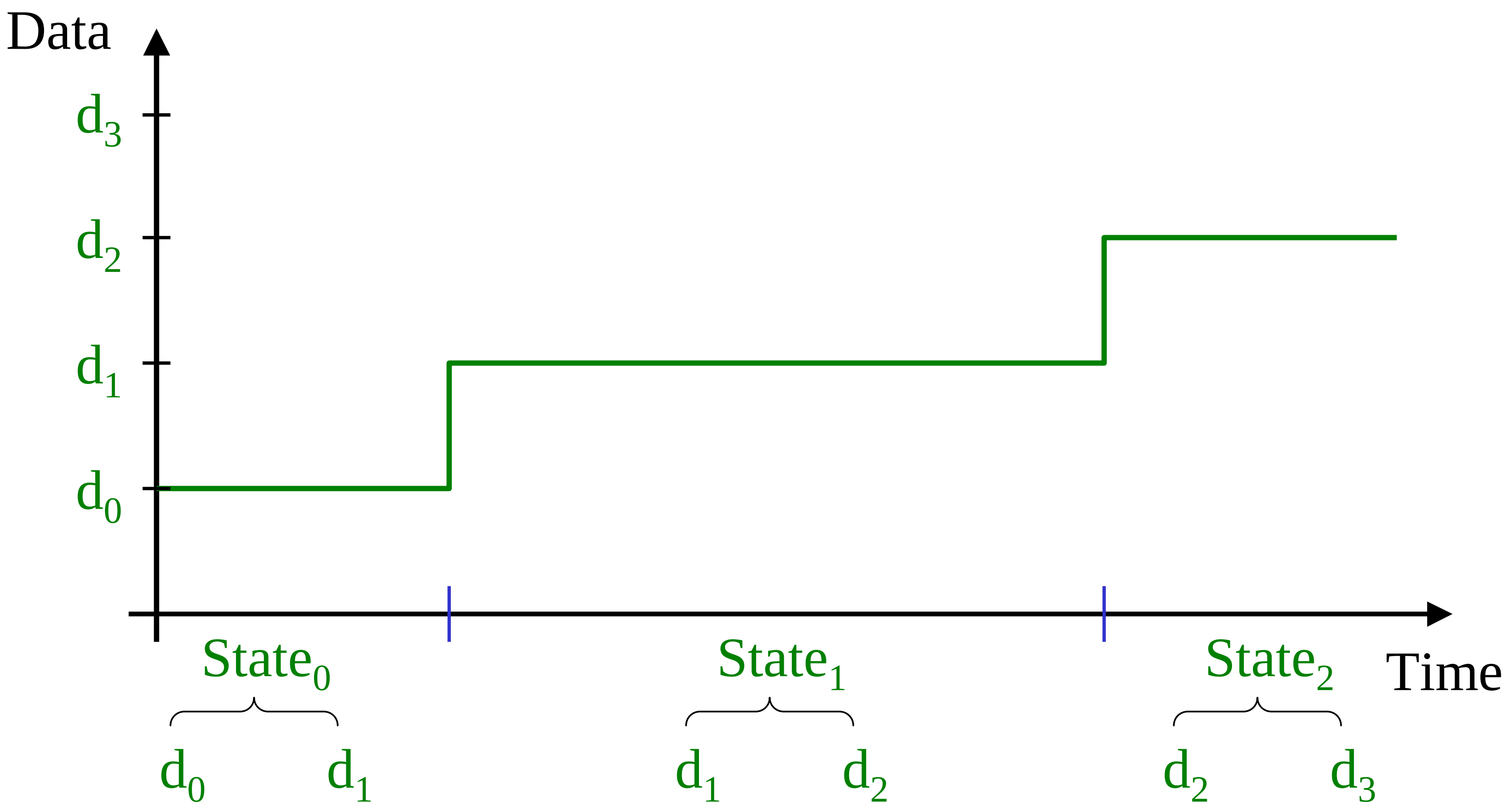
Real World



Discrete Data

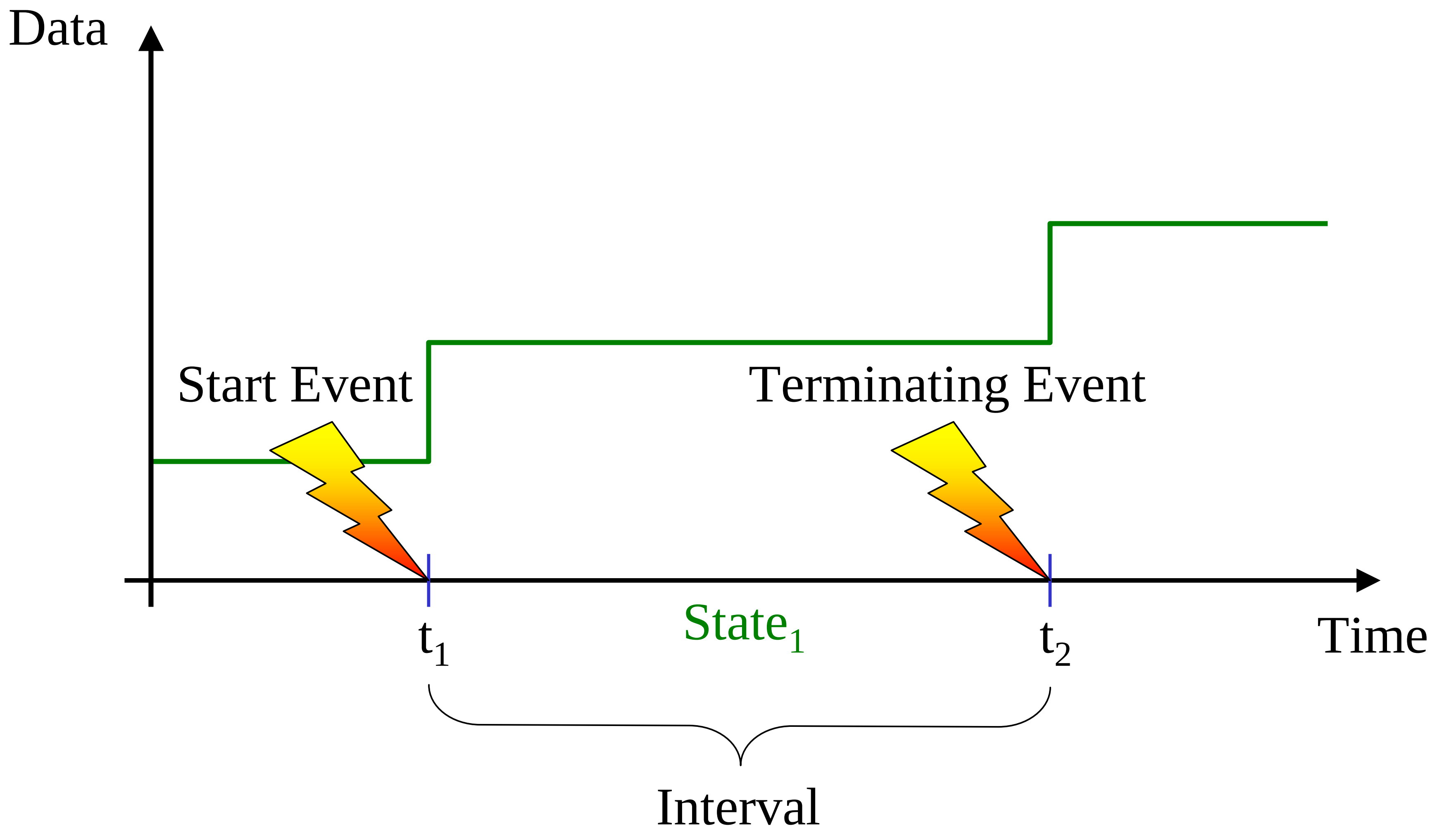


State

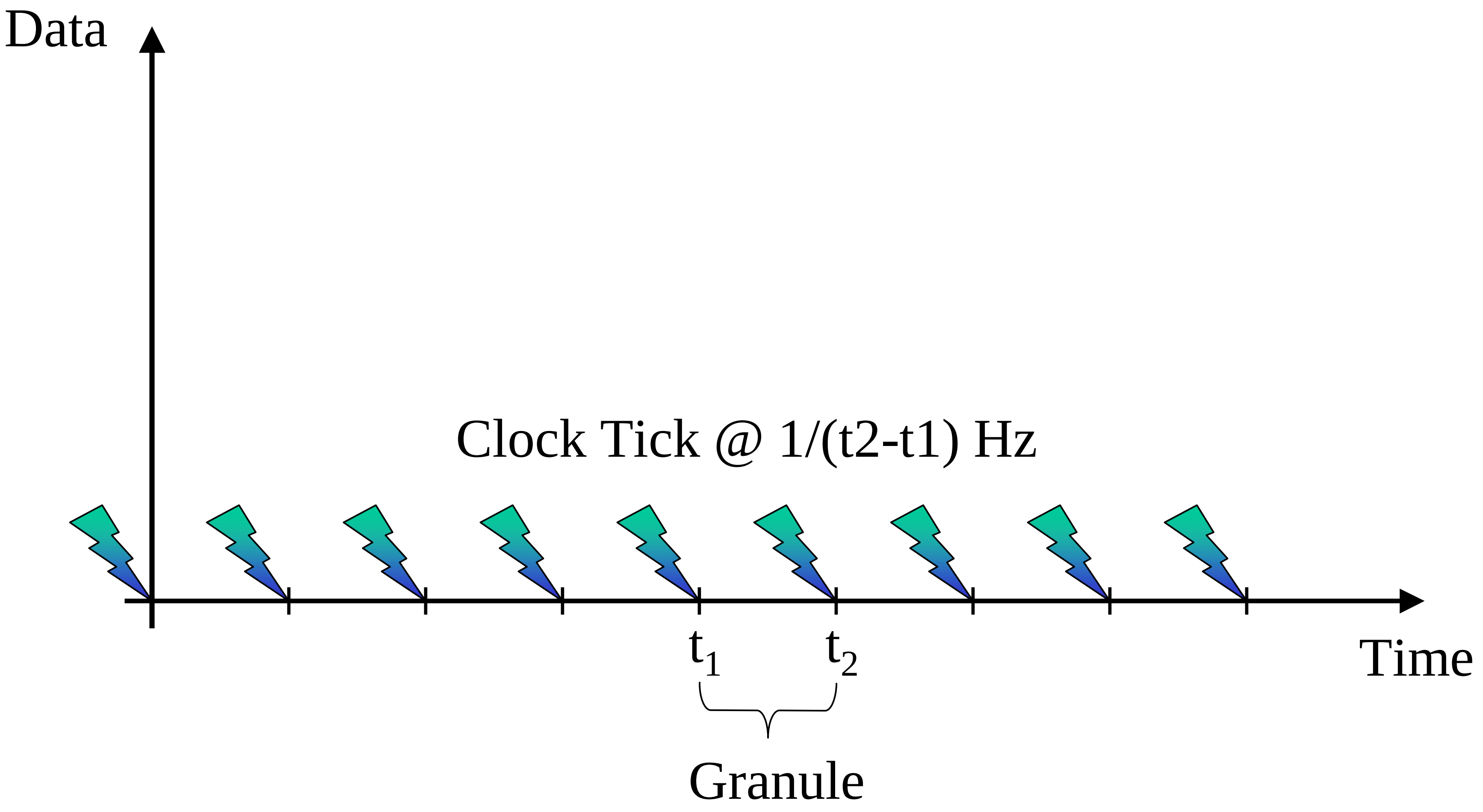


Data
d_3
d_2
d_1
d_0
Time
State_0
d_0 d_1
State_1
d_1 d_2
State_2
d_2 d_3

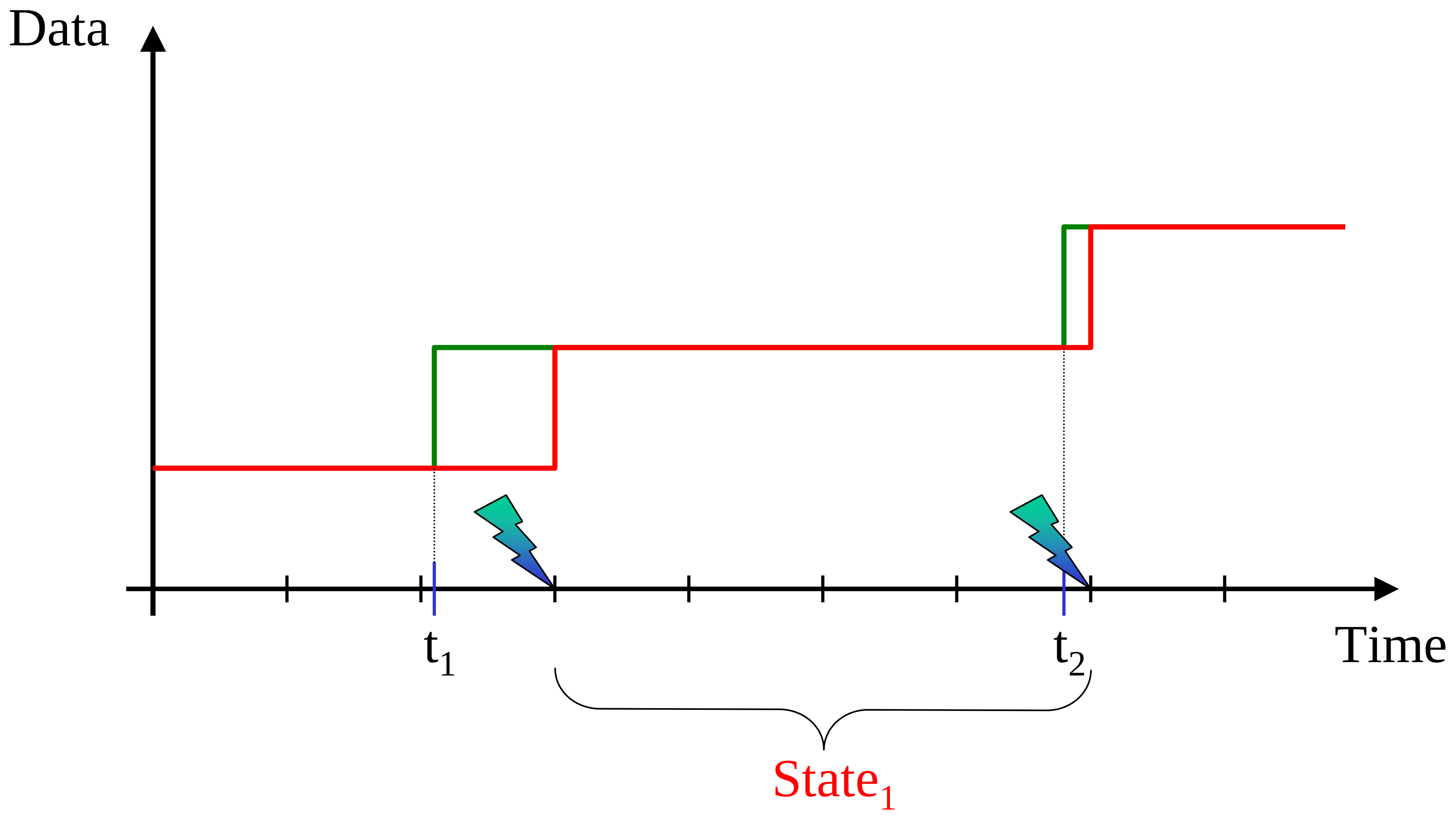
Continuous Time



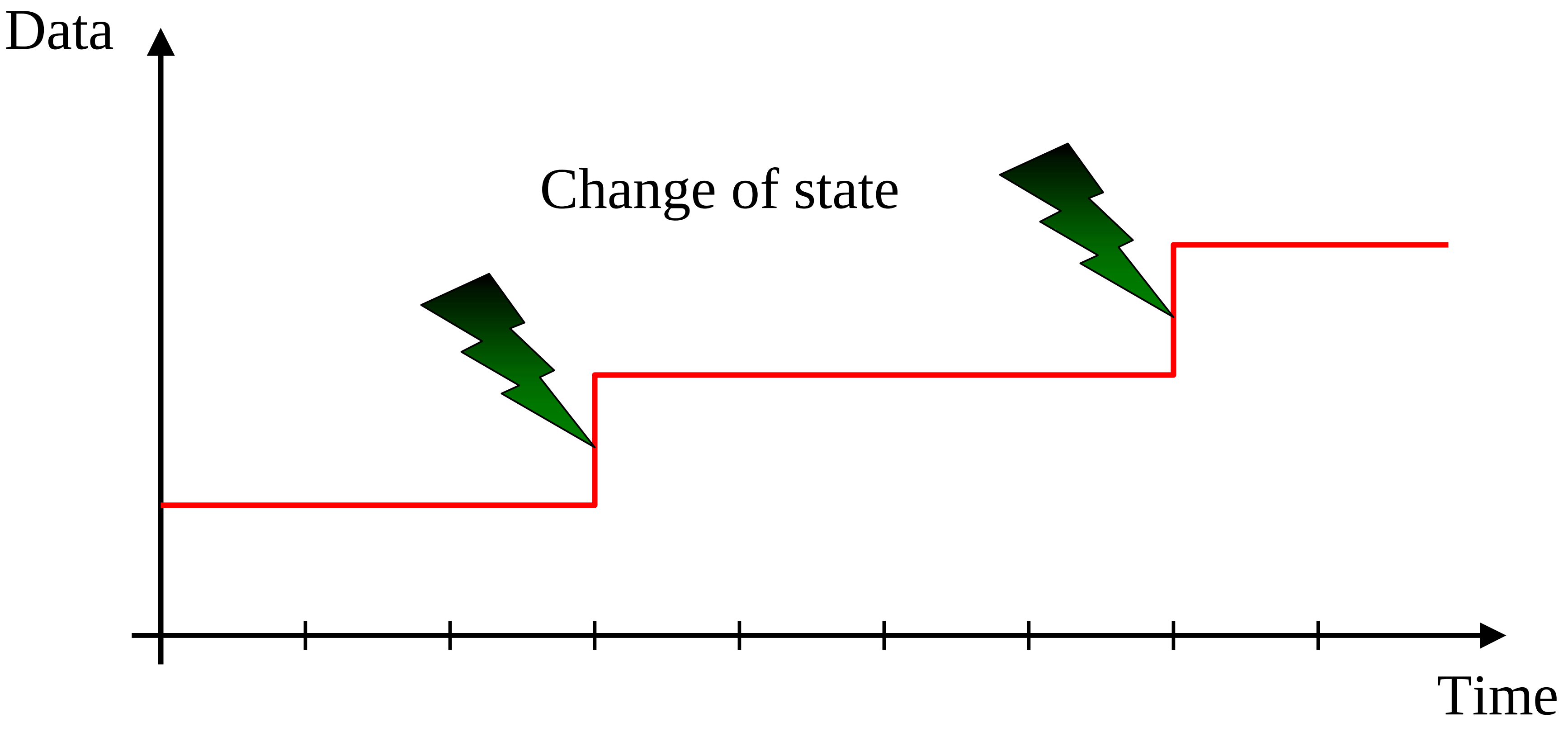
Digital Clock



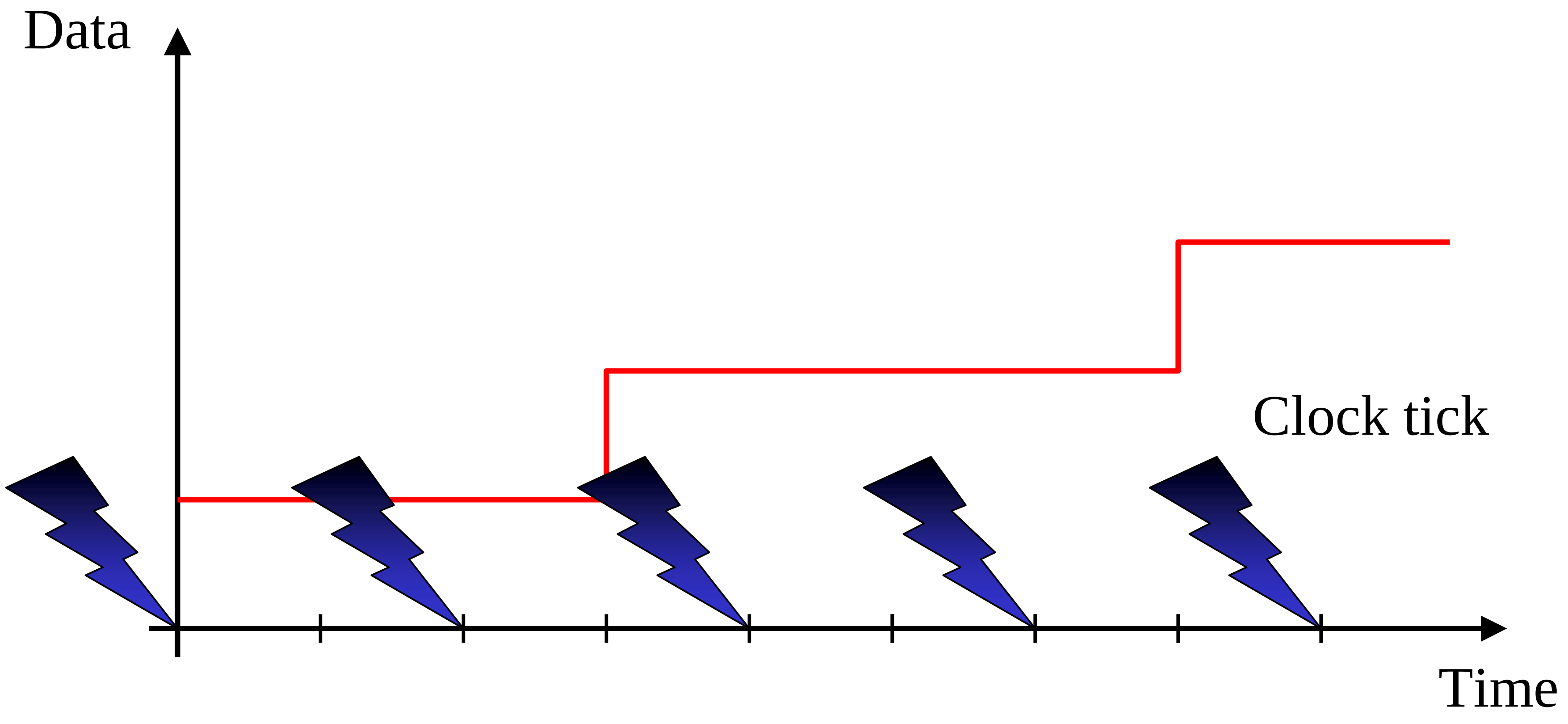
Discrete Time



Event-Triggered (ET) System



Time-Triggered (TT) System

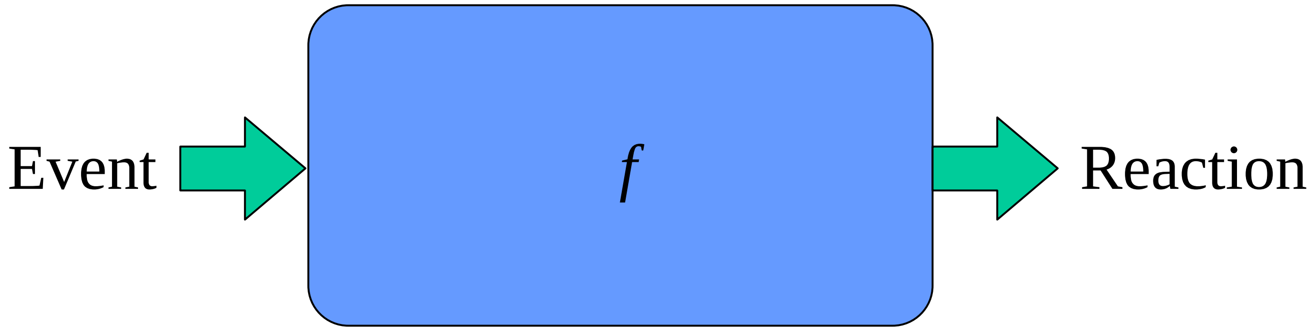


Esterel - Giotto

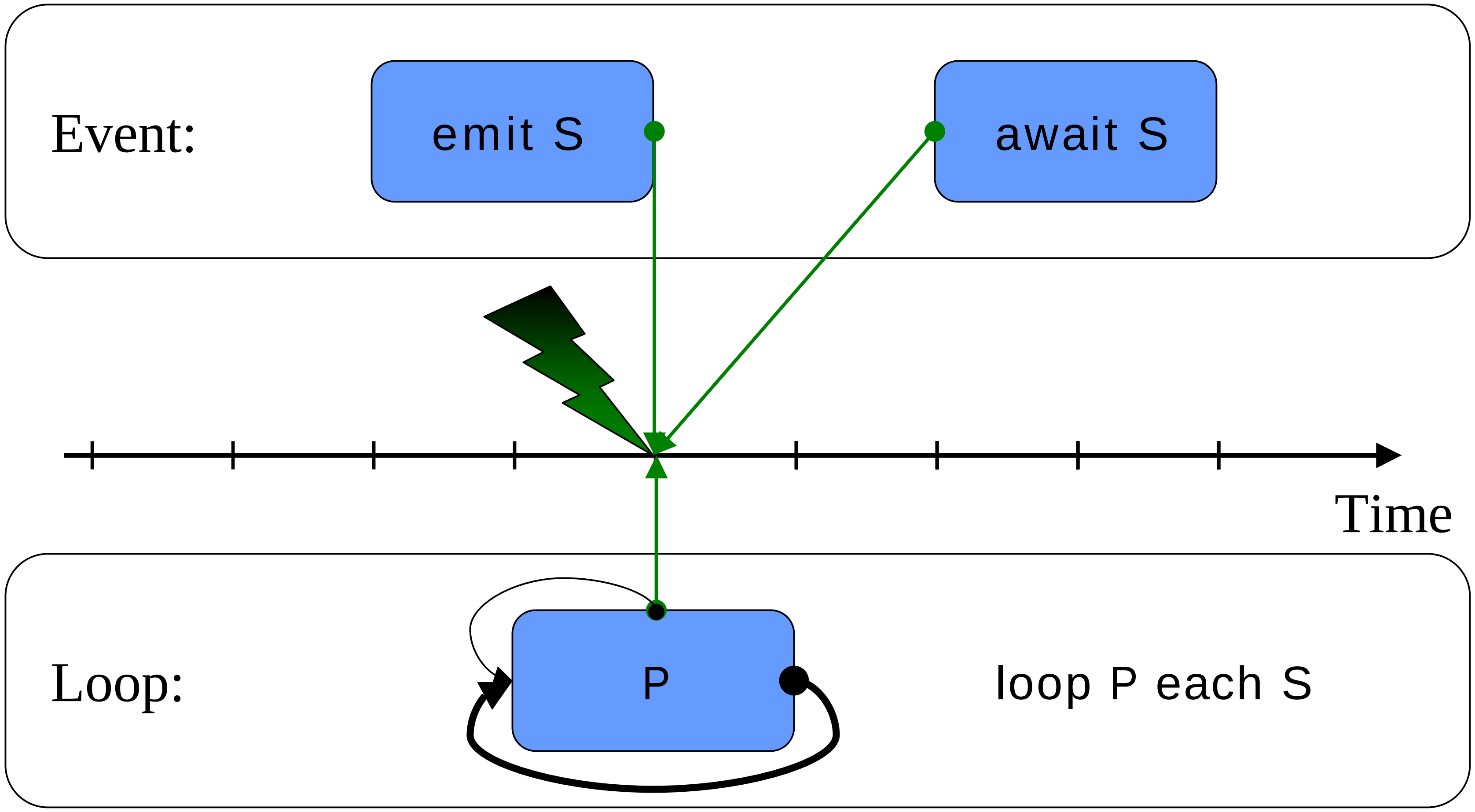
- Esterel:
  - Synchronous reactive language
  - Event-triggered semantics

- Giotto:
  - Time-triggered semantics
  - Distributed platforms

Event - Reaction

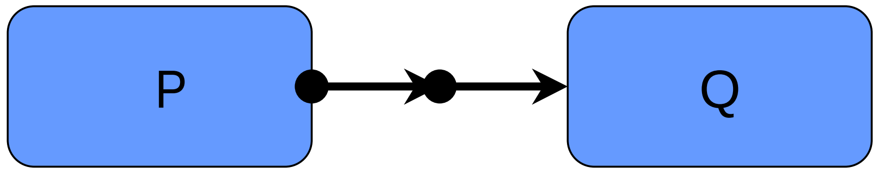


Esterel: Event



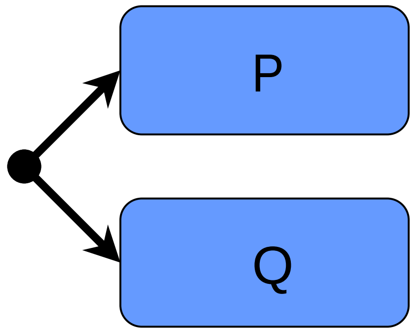
Esterel: Operators

Sequential:



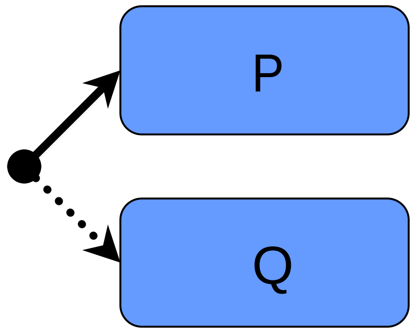
P ; Q

Parallel:



P || Q

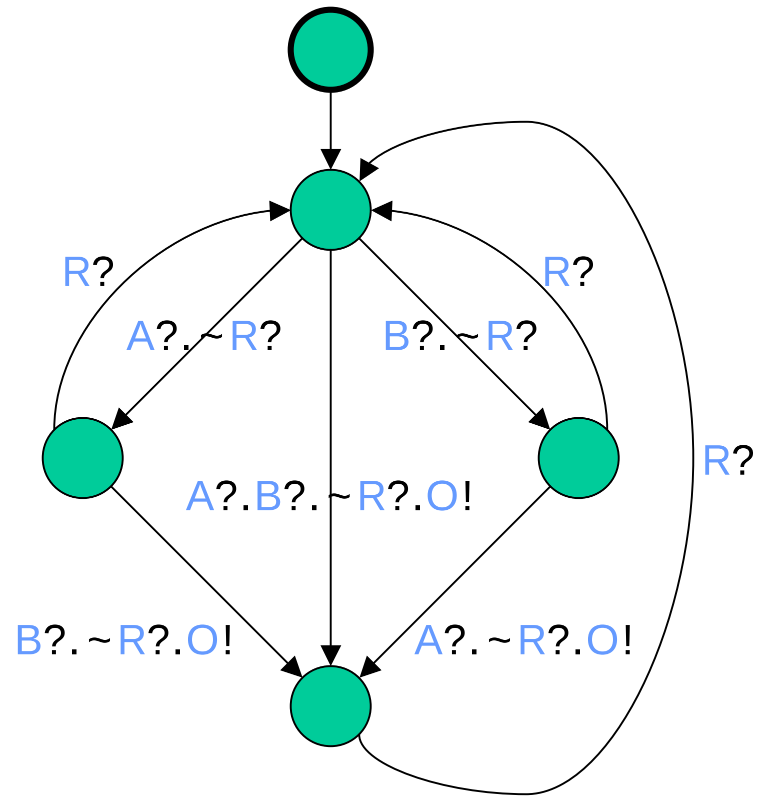
Choice:



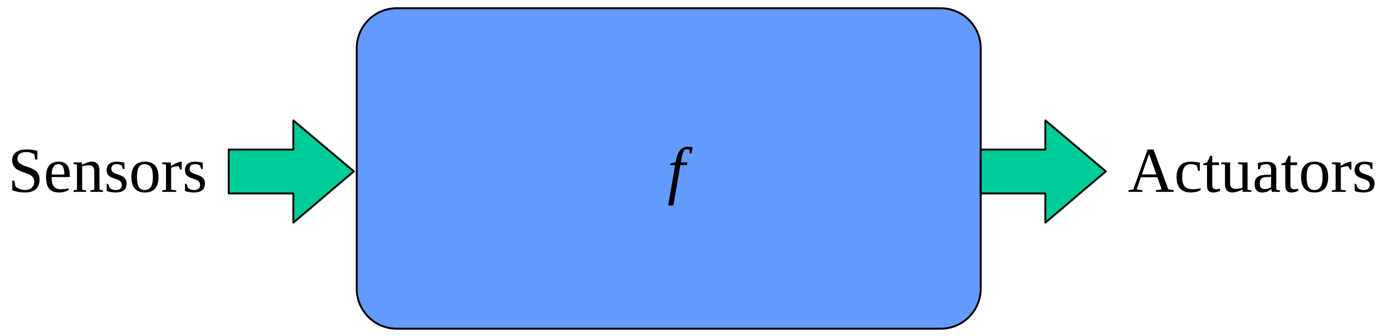
present S then P else Q

Esterel: Controller

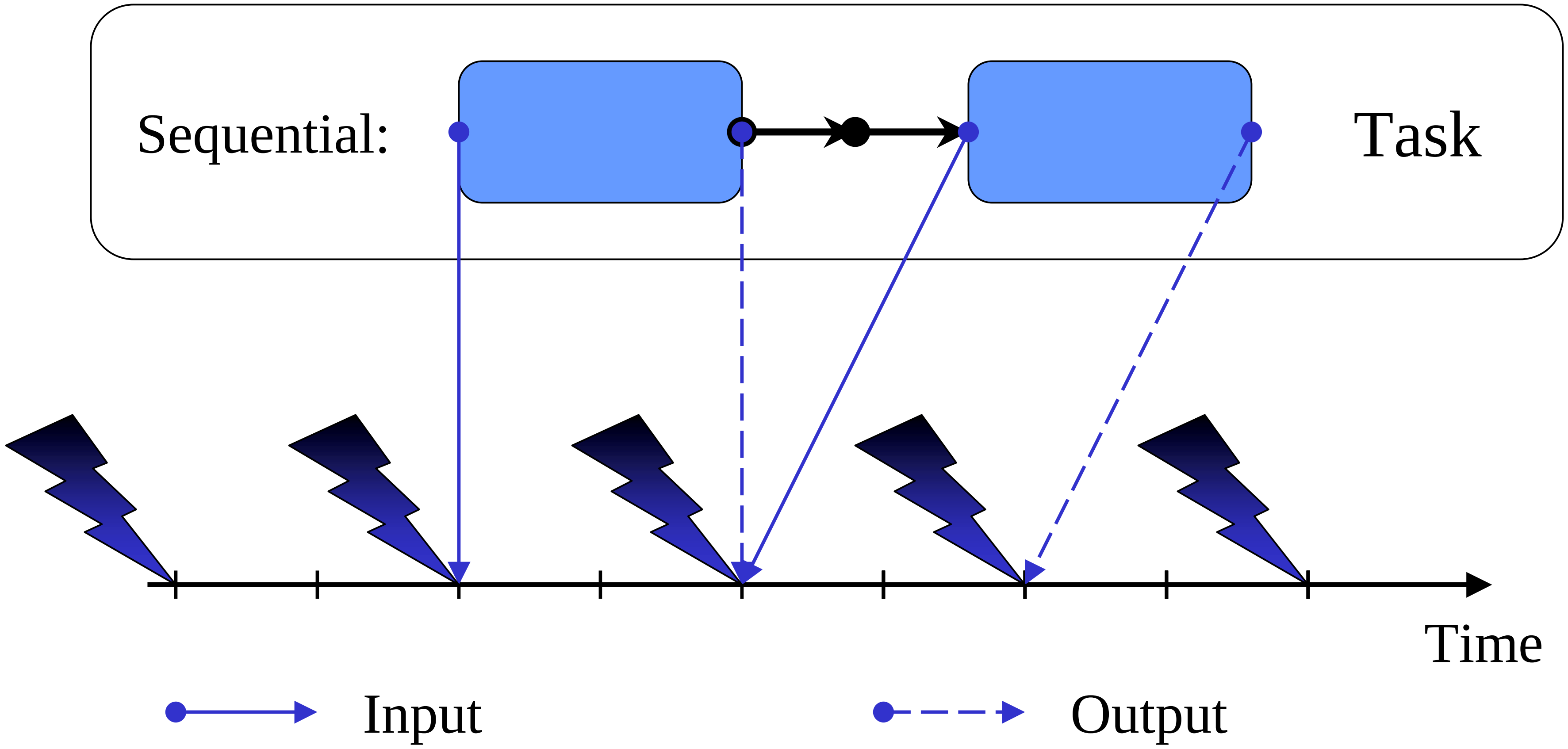
```
module normal:
  input A, B, R;
  output O;
    loop
      [ await A || await B ];
      emit O
    each R
end module
```



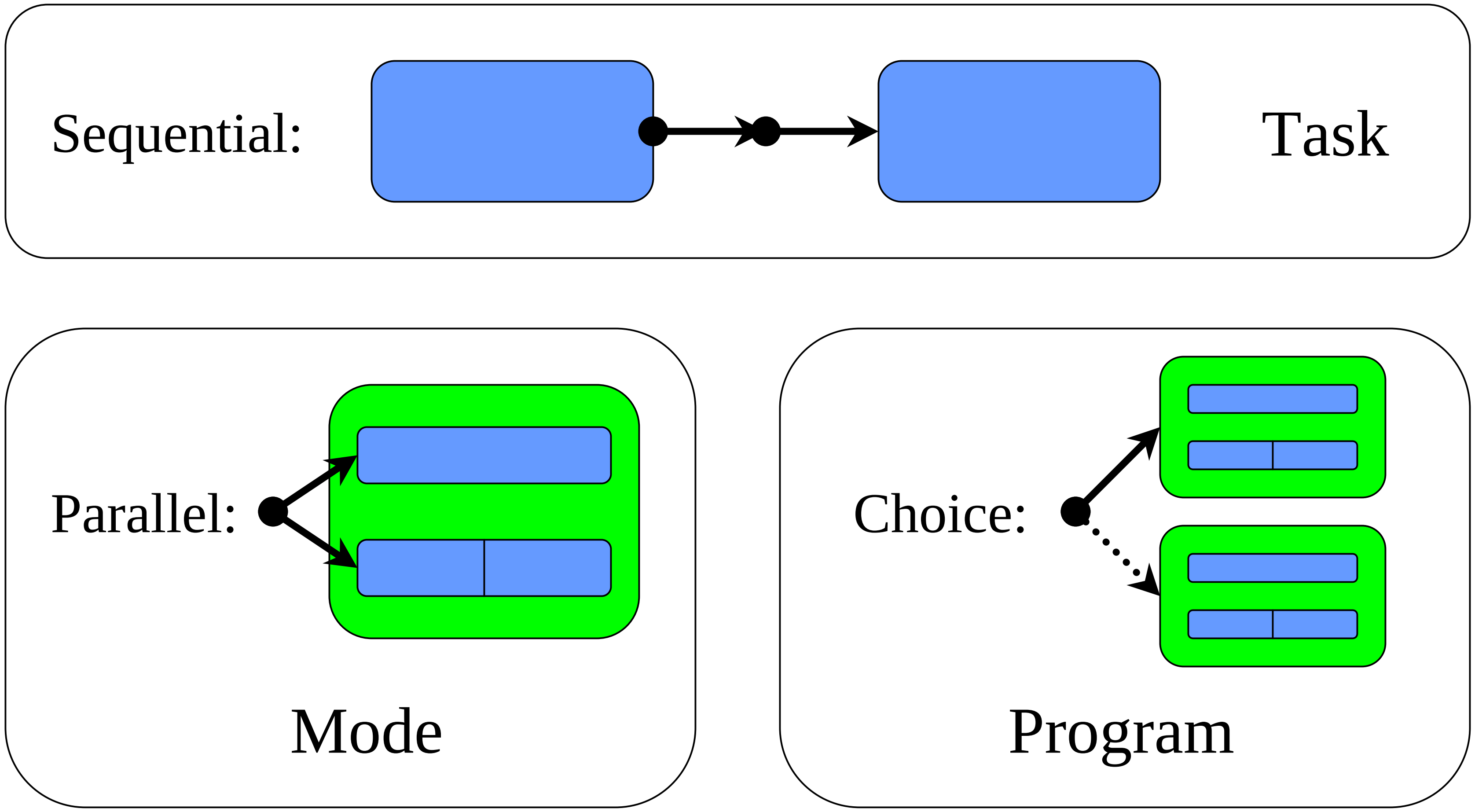
Sensor - Control Law - Actuator



Giotto: Time



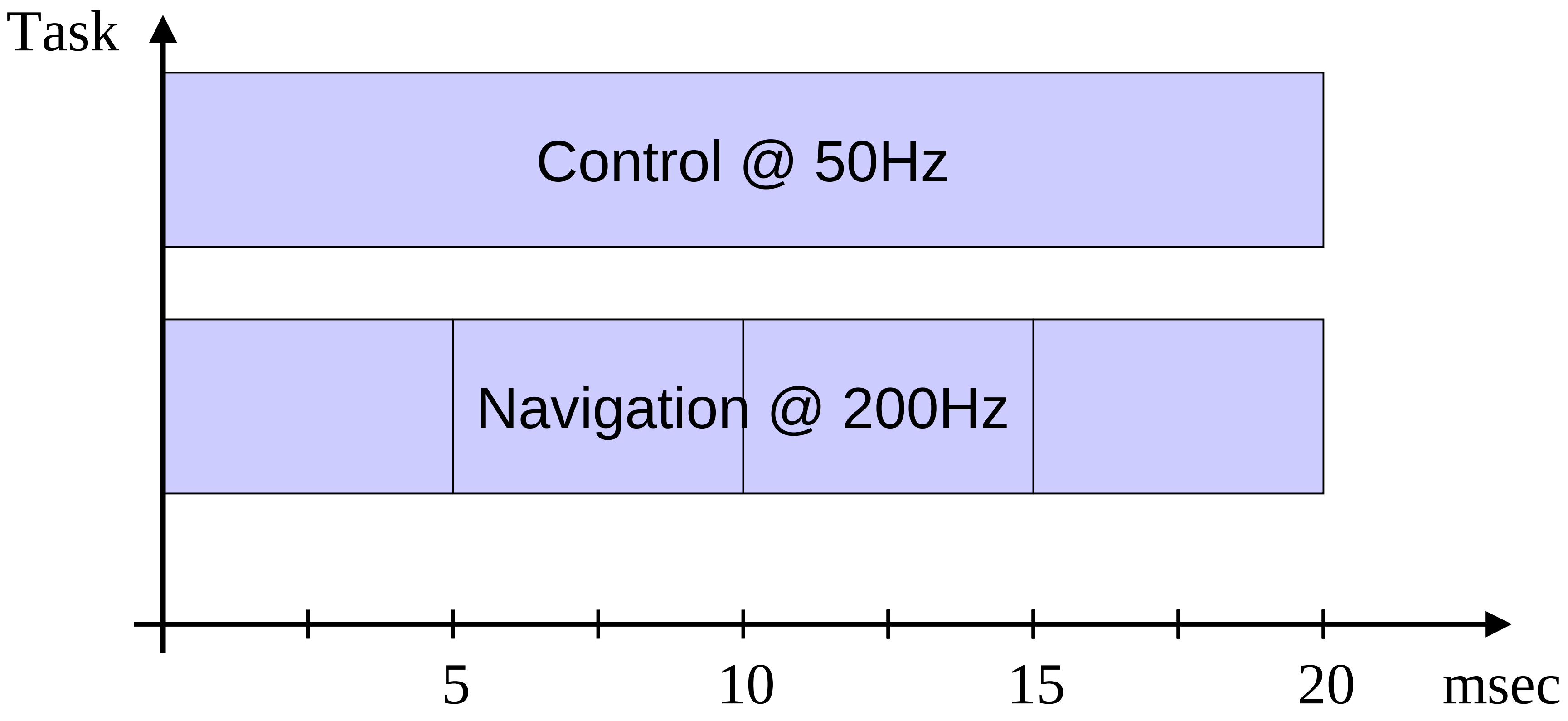
Giotto: Operators



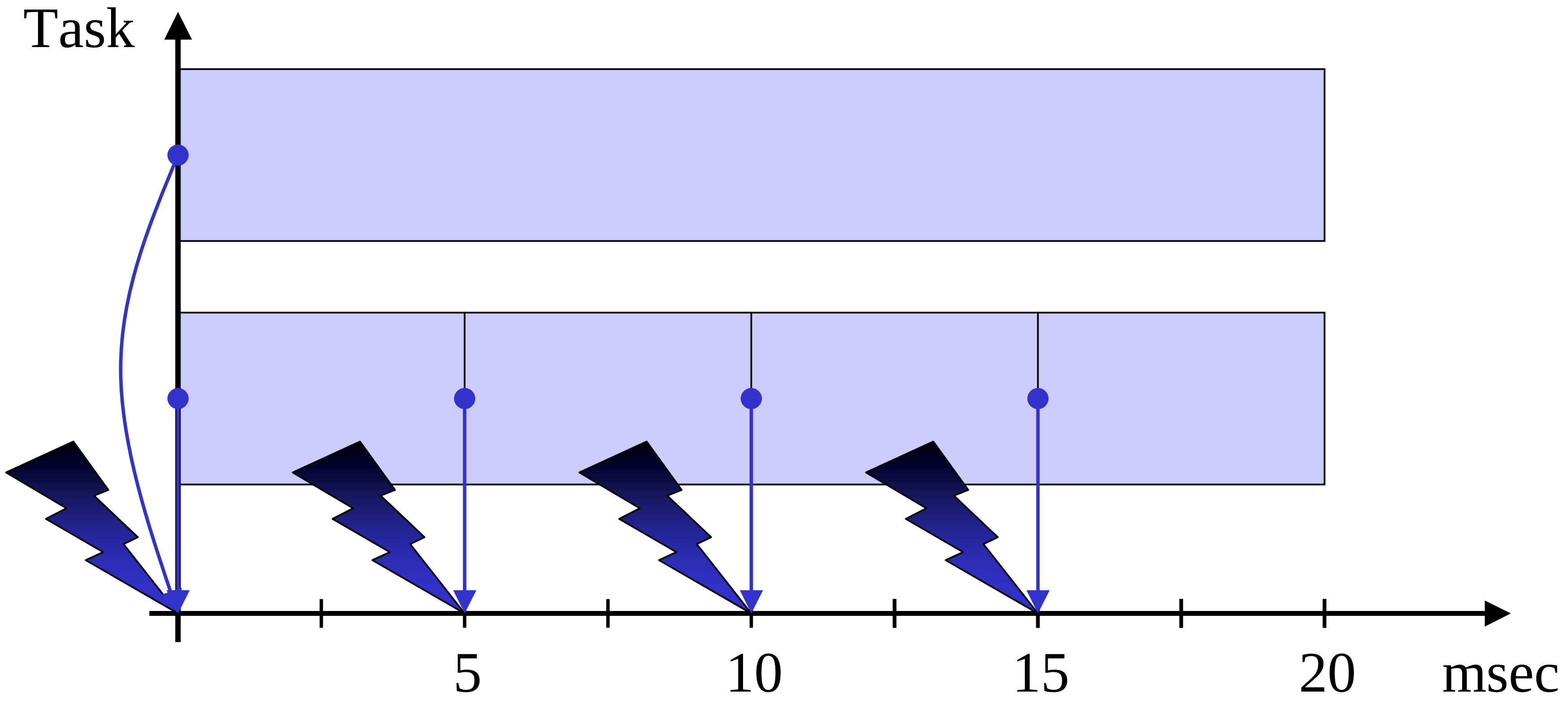
Giotto: Helicopter Control

```
mode normal ( ) period 20ms
  {
      taskfreq 1 do servo = Control ( position ) ;
      taskfreq 4 do position = Navigation ( GPS, position ) ;
  }
```

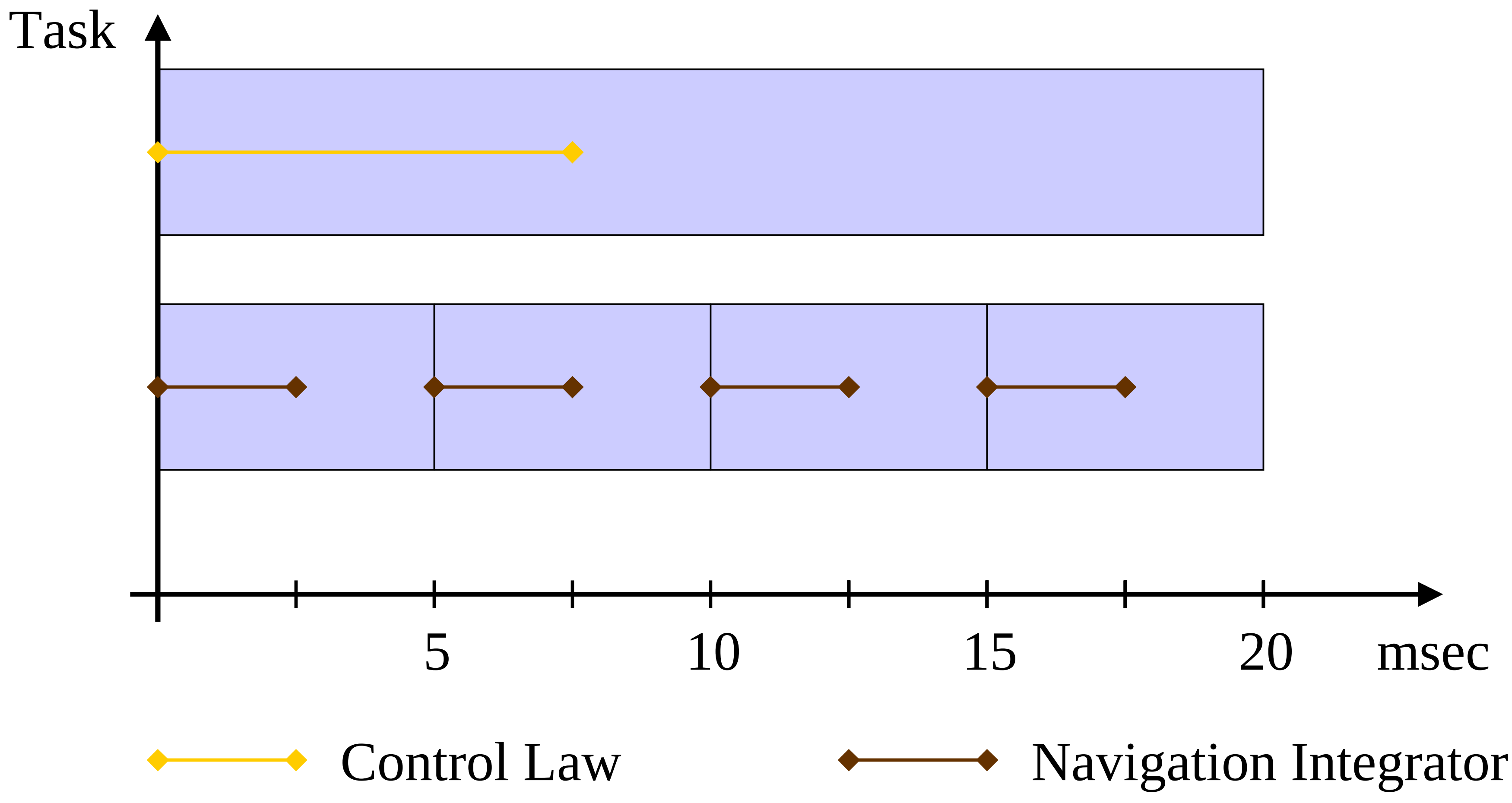
Semantics



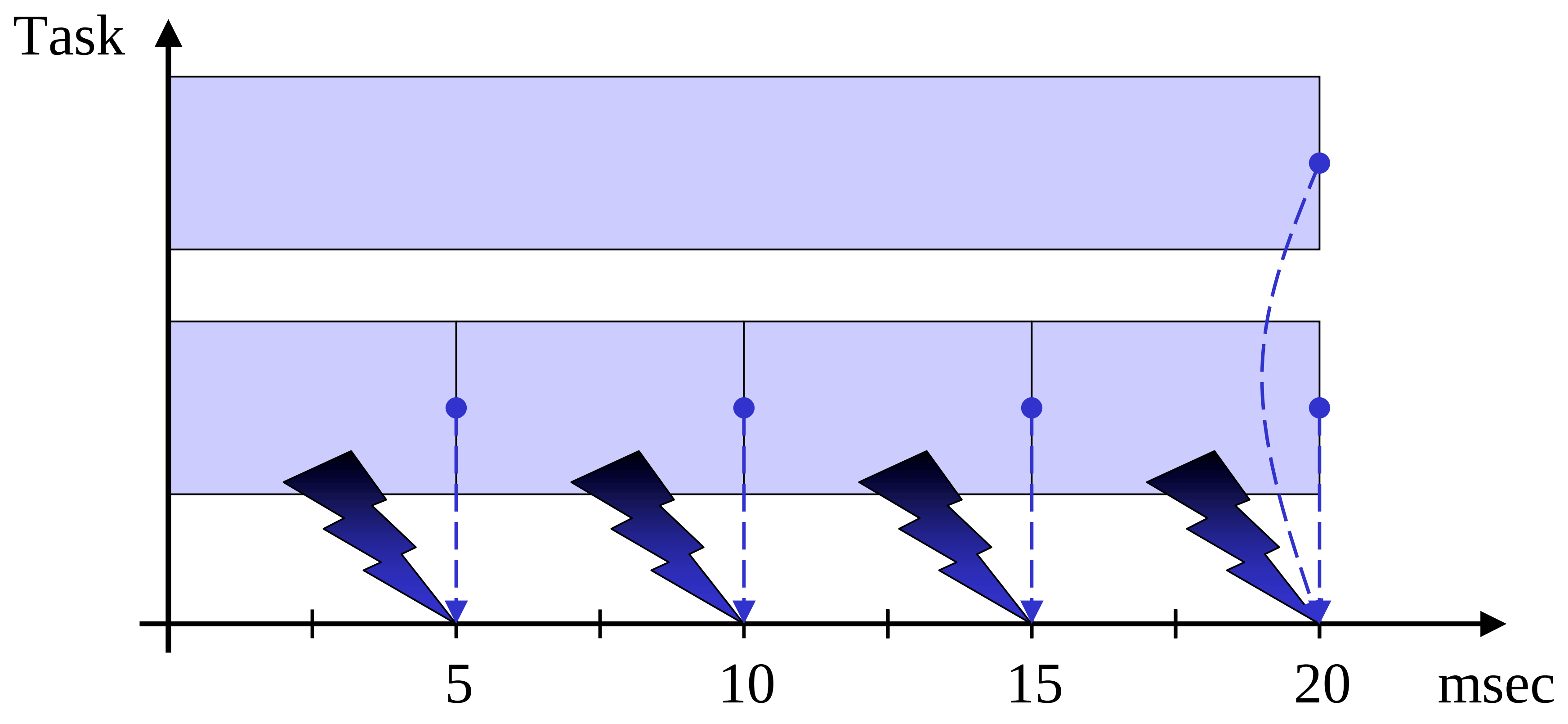
Input



Computation



Output



Literature

- Esterel:
  - The Foundations of Esterel. G. Berry. In Proof, Language and Interaction: Essays in Honour of Robin Milner. G. Plotkin, C. Stirling and M. Tofte, editors. MIT Press, 2000.
  - Synchronous programming of reactive systems. N. Halbwachs. Kluwer, 1993.
- Giotto:
  - Embedded Control Systems Development with Giotto. B. Horowitz, T. Henzinger, C. Kirsch. 2001.
  - Giotto: A Time-Triggered Language for Embedded Programming. B. Horowitz, T. Henzinger, C. Kirsch. 2001.

Embedded Programming

…requires the integration of:

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3. Embedded compilers
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5. Formal methods

Concurrency

$\boxed{\text{Parallel Composition}}$

Task1 $\parallel$ Task2

$$\Downarrow$$

Task1 ; Task2

Task2 ; Task1

$\boxed{\text{I/O Decomposition}}$

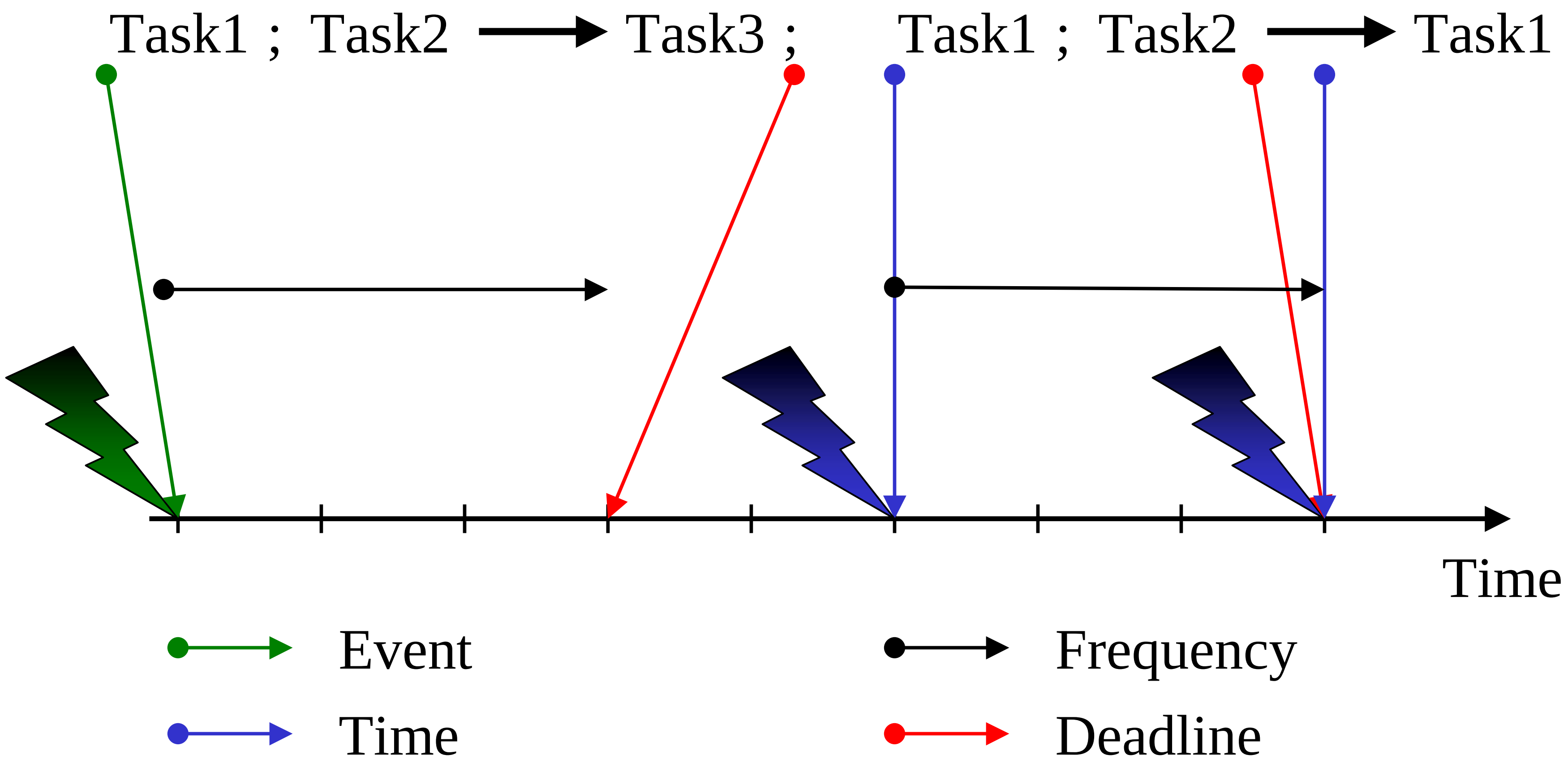
Task1 $\longleftrightarrow$ Task2

$$\Downarrow$$

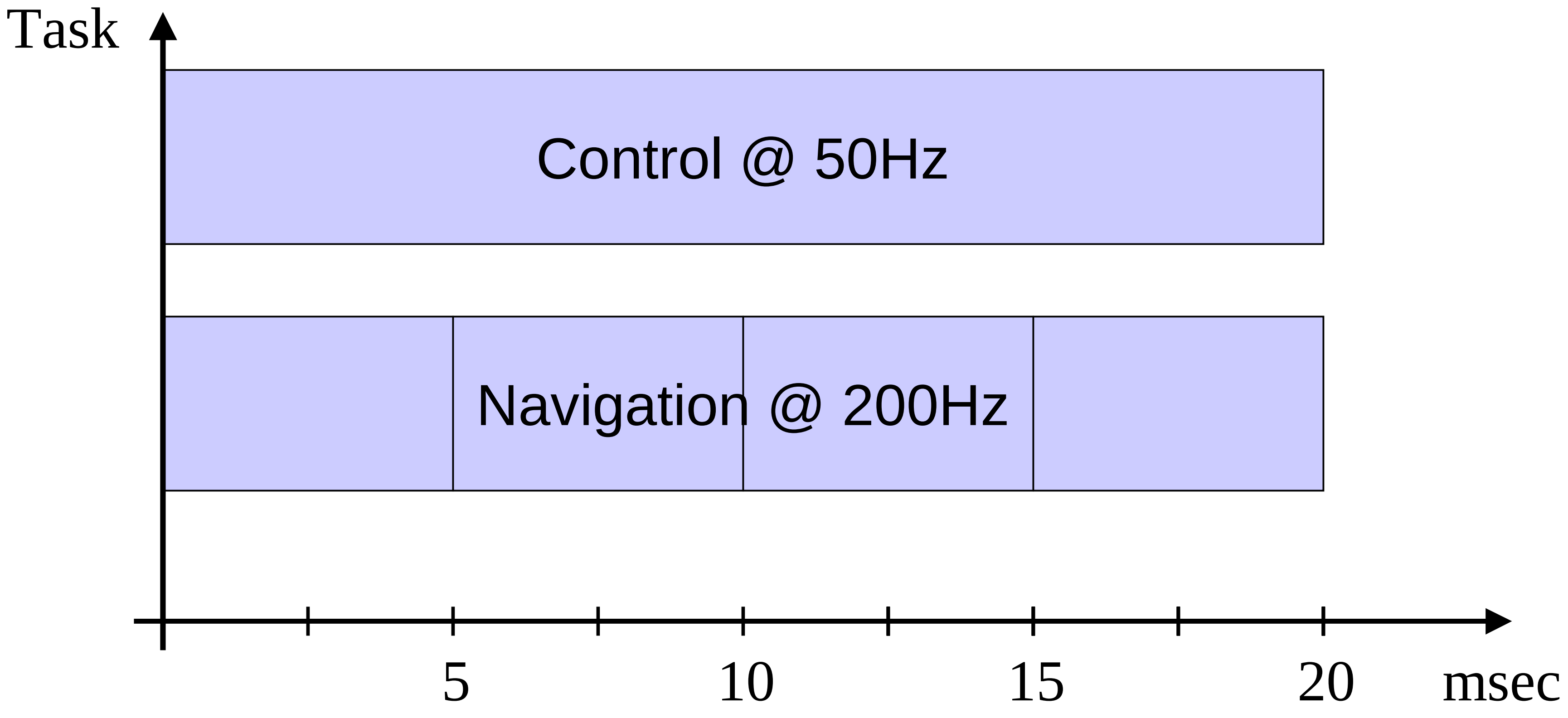
Task1 $\longrightarrow$ Task2

Task2 $\longrightarrow$ Task1

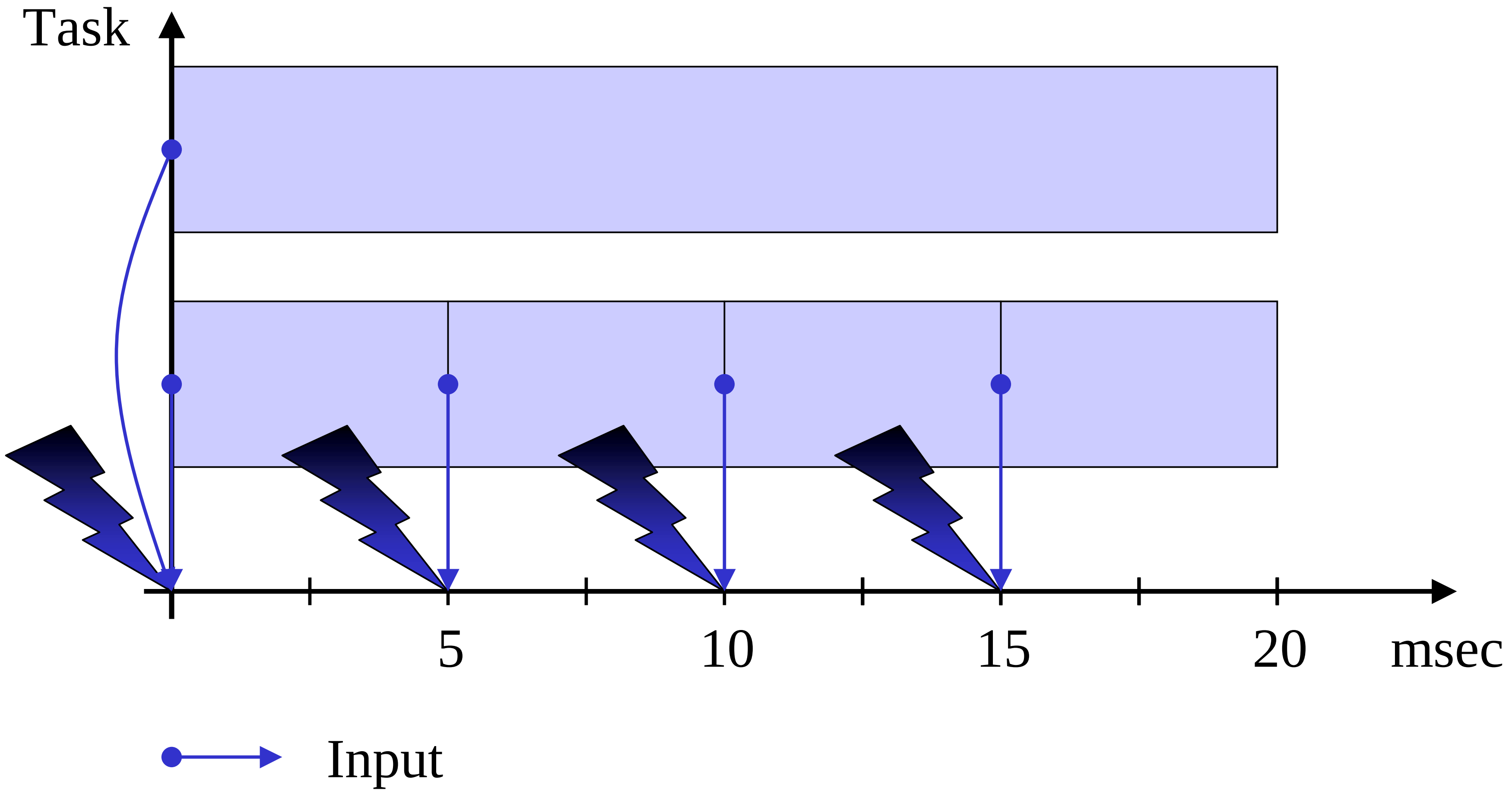
Real-Time


Task1 ; Task2
Task3 ;
Task1 ; Task2
Task1
Time
Event
Frequency
Time
Deadline

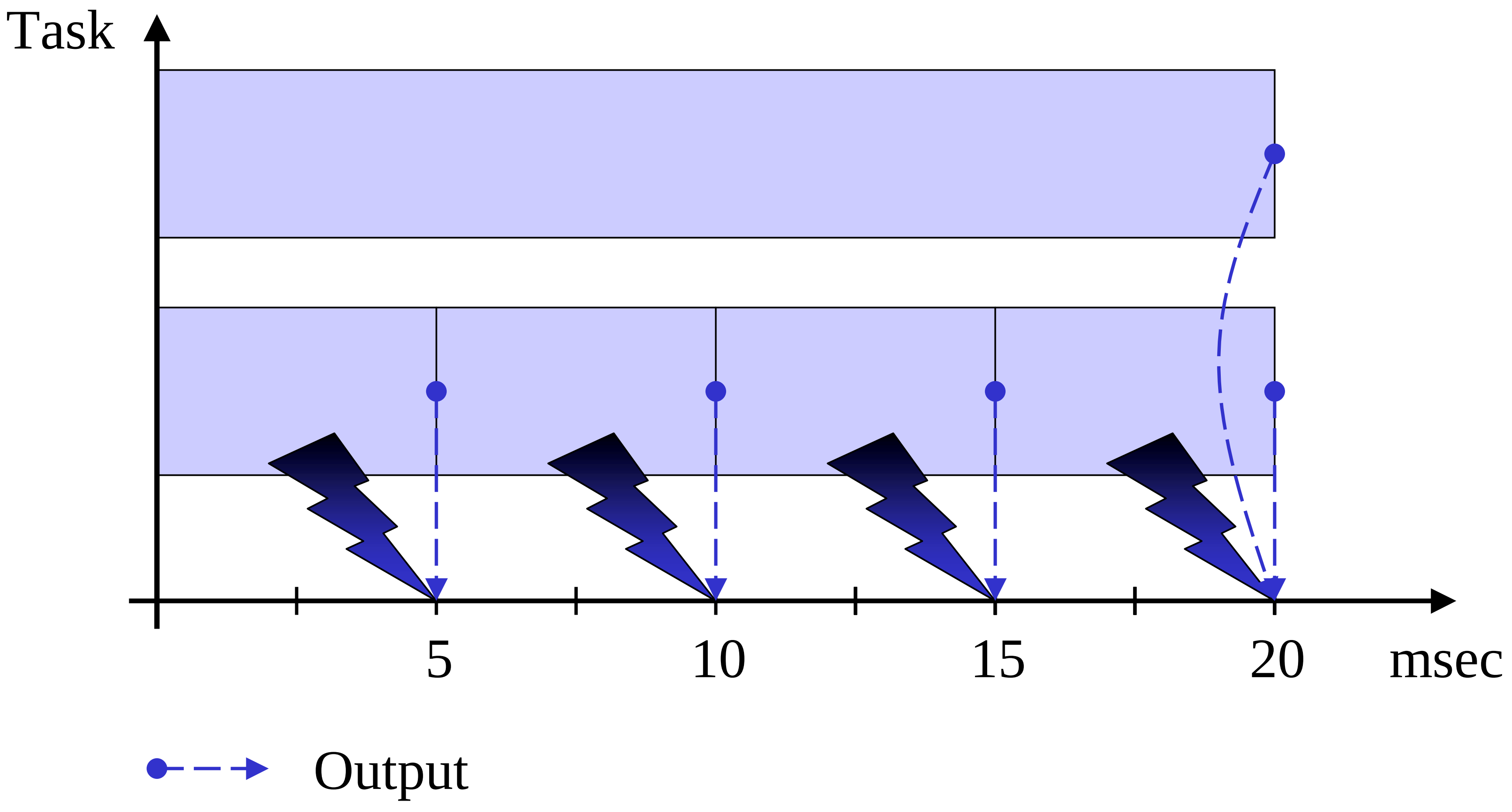
Helicopter Control



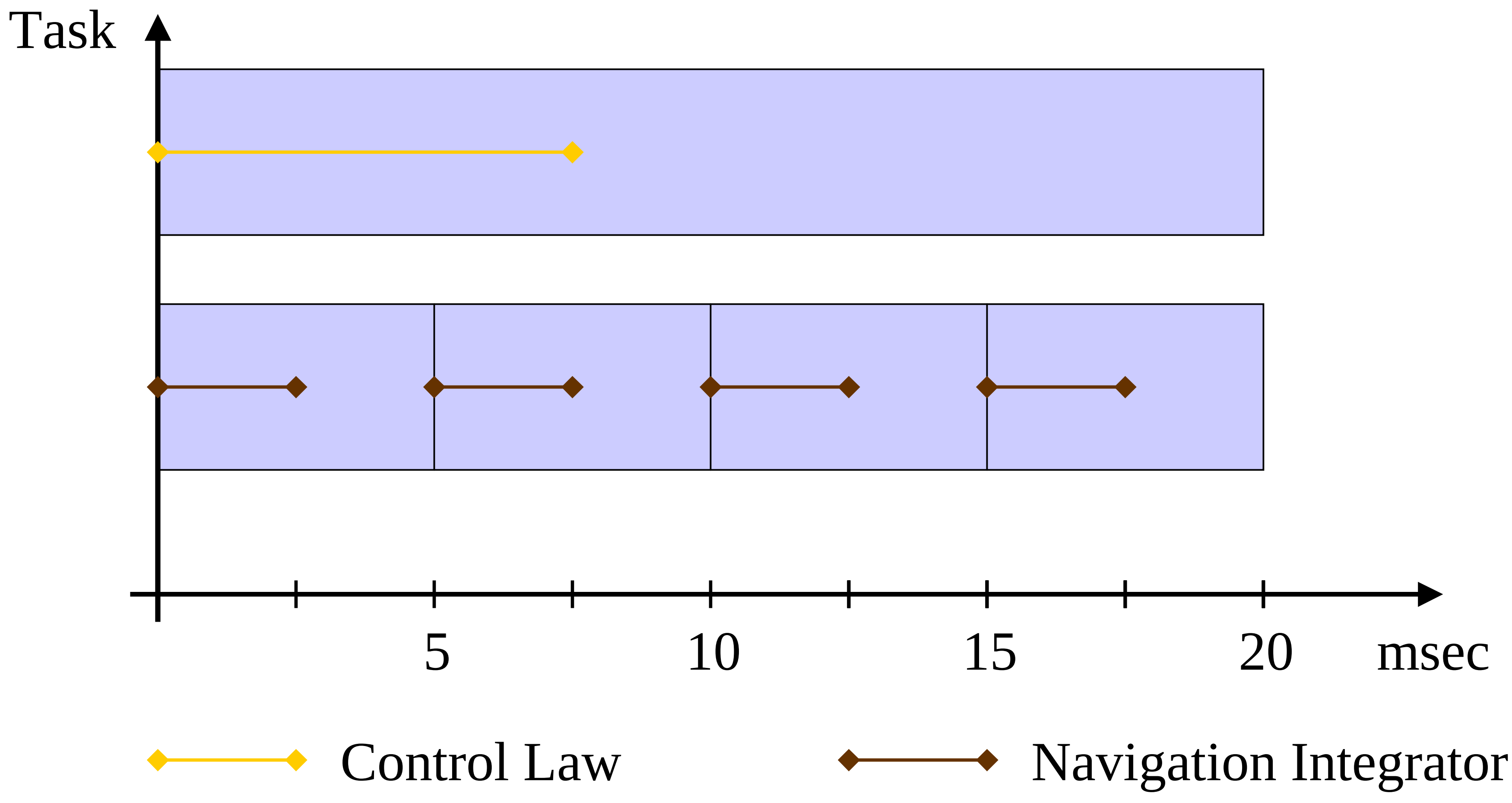
Read



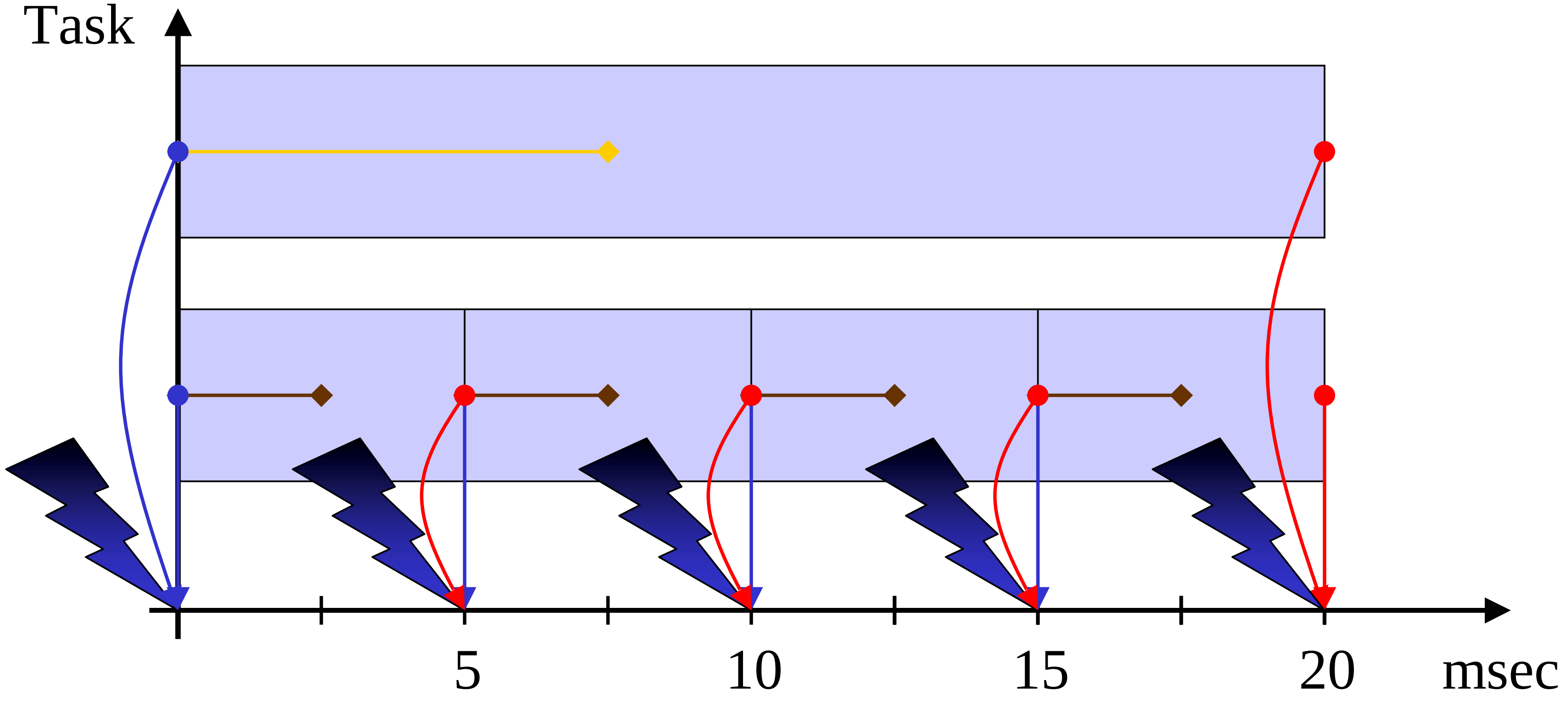
Write



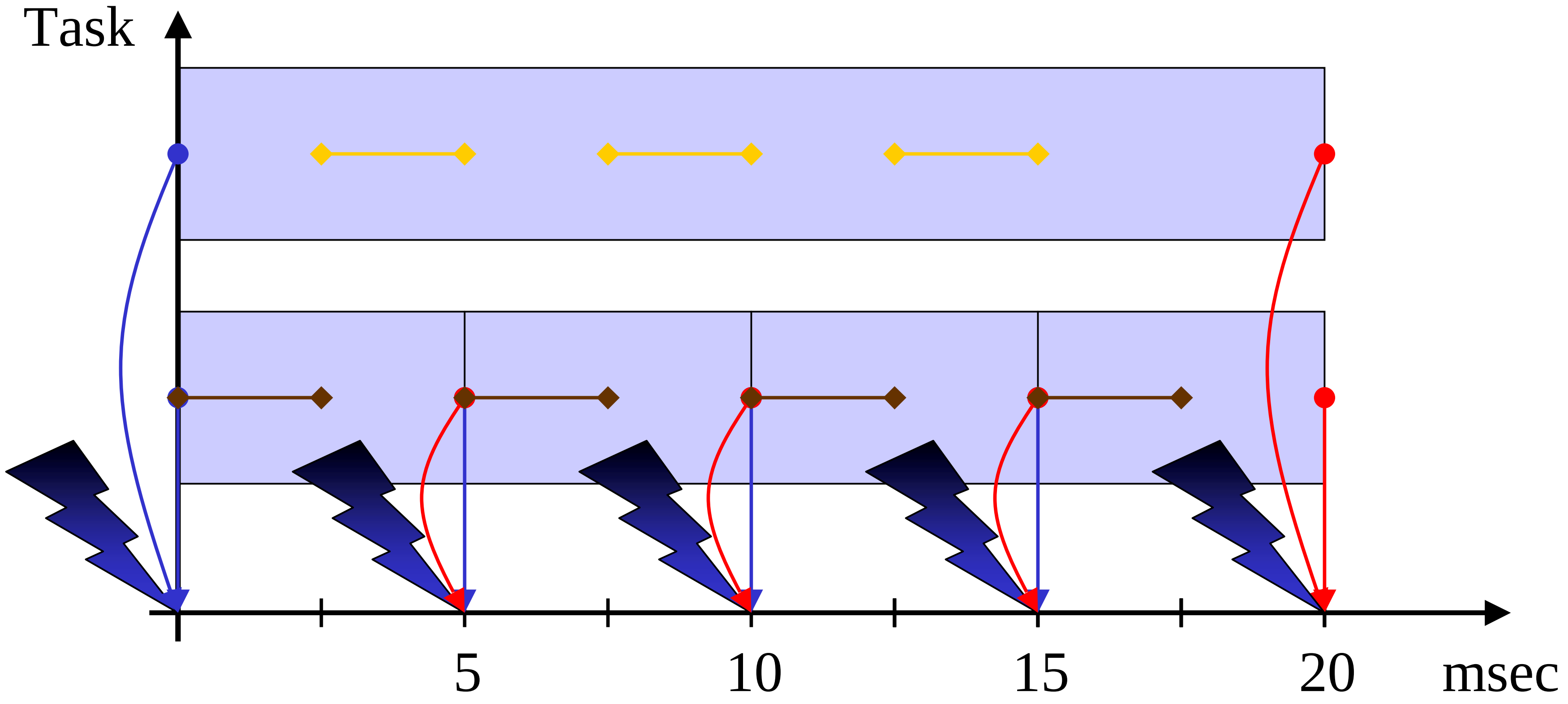
Worst Case Execution Time

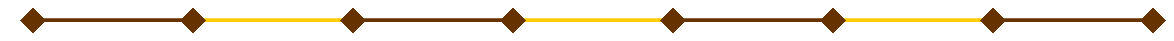


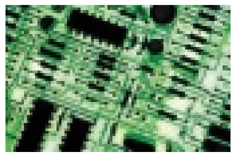
Deadline



Code







Literature

- Some compiler books:
  - Compiler Construction, N. Wirth, Addison-Wesley, 1996.
  - Compilers, Principles, Techniques, and Tools. A.V. Aho, R. Sethi, J.D. Ullman. Addison-Wesley, 1985.
  - Compiler Design. R. Wilhelm, D. Maurer. Addison-Wesley, 1995.

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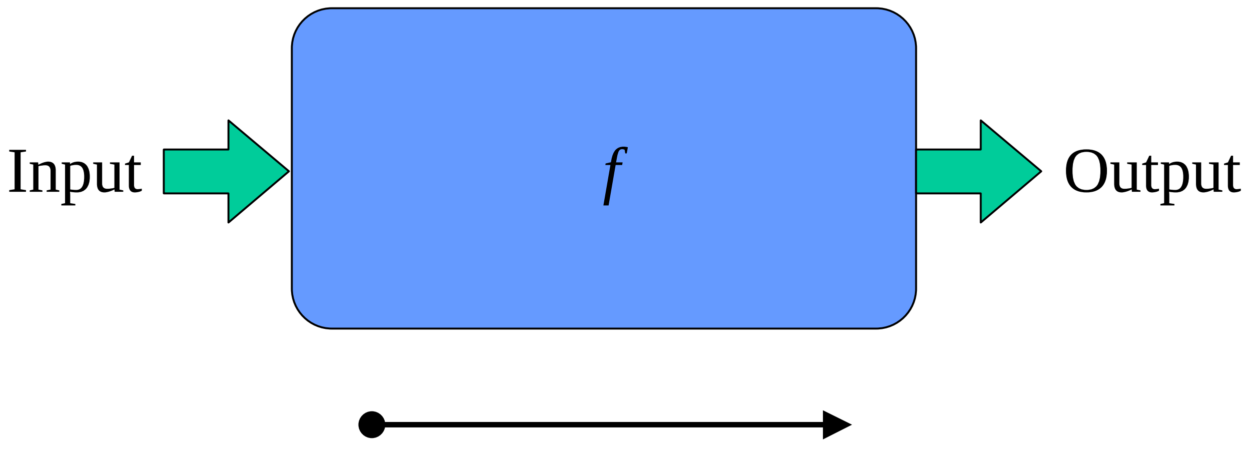
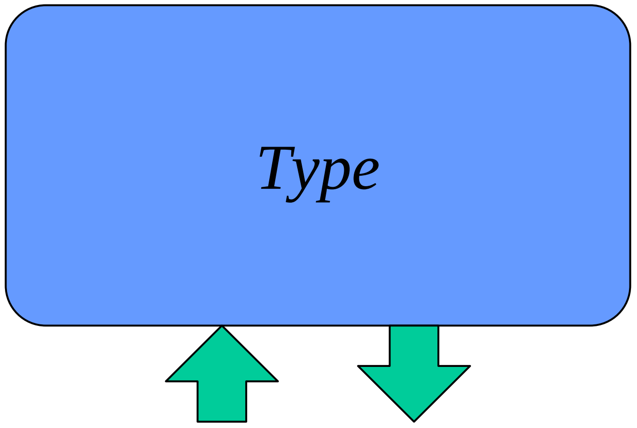
Real-Time Task



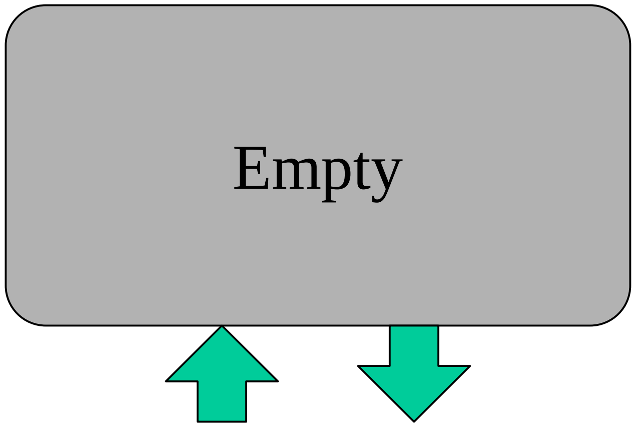
Worst case execution time

Abstract Data Type



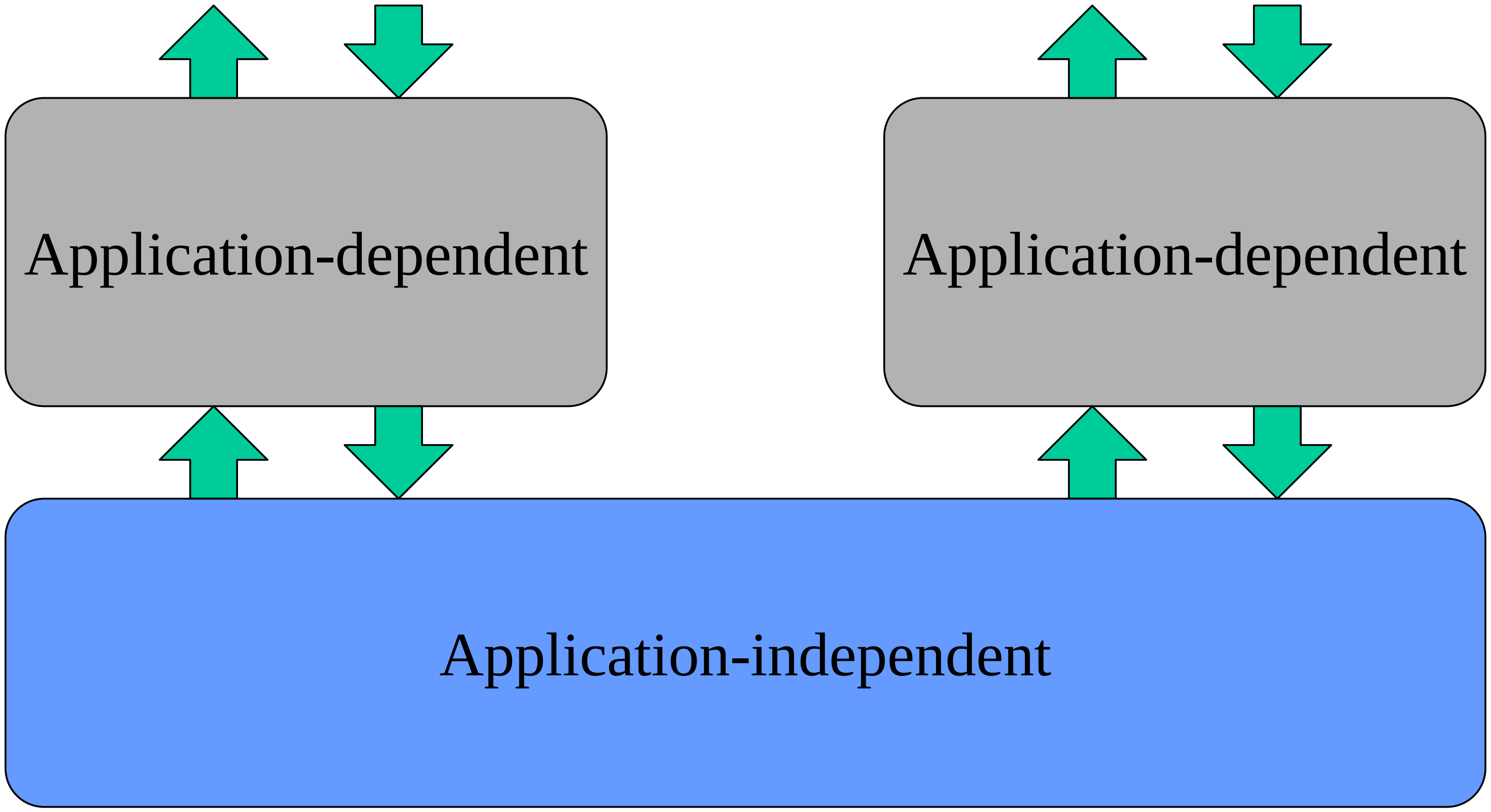
Interface: Set of methods

Abstract Interface

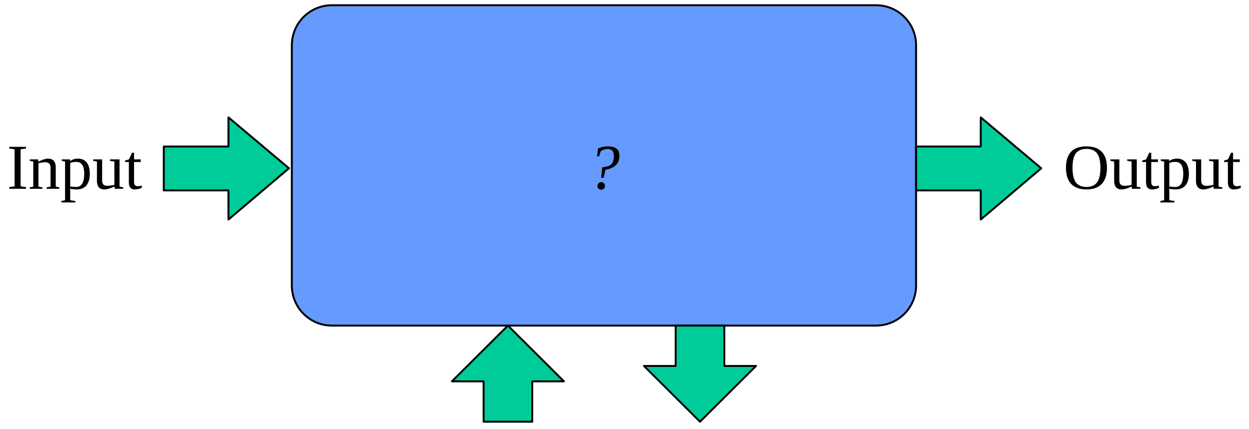


Interface: Set of methods

Framework


Application-dependent
Application-dependent
Application-independent

Type vs. Task



Interface: Set of methods

Literature

- Patterns & Frameworks:
  - Design Patterns: Elements of Reusable Object Oriented Software. E. Gamma, J. Vlissides, R. Johnson, R. Helm. Addison Wesley, 1994.
  - Design Patterns for Object-Oriented Software Development. W. Pree, E. Gamma. Addison Wesley, 1995.

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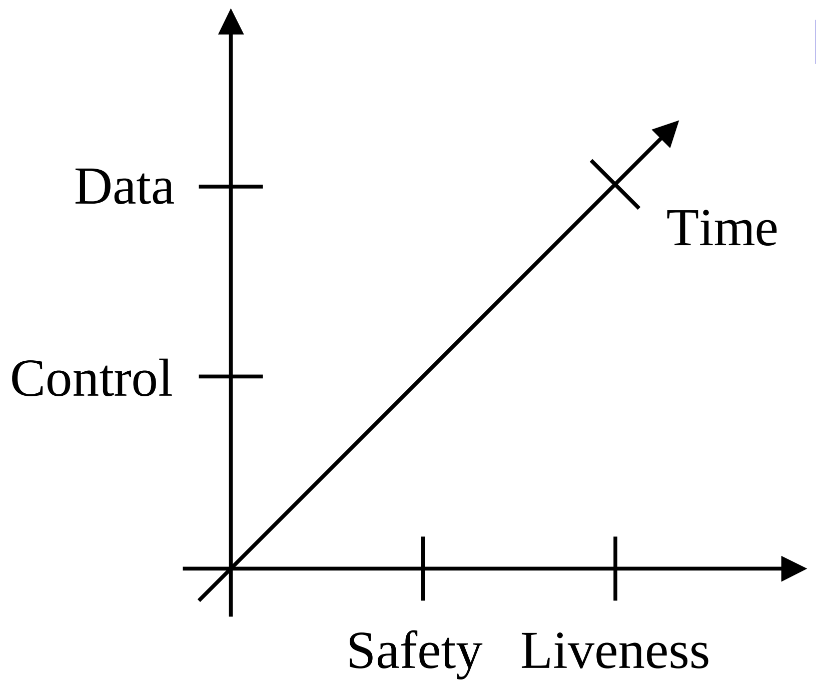
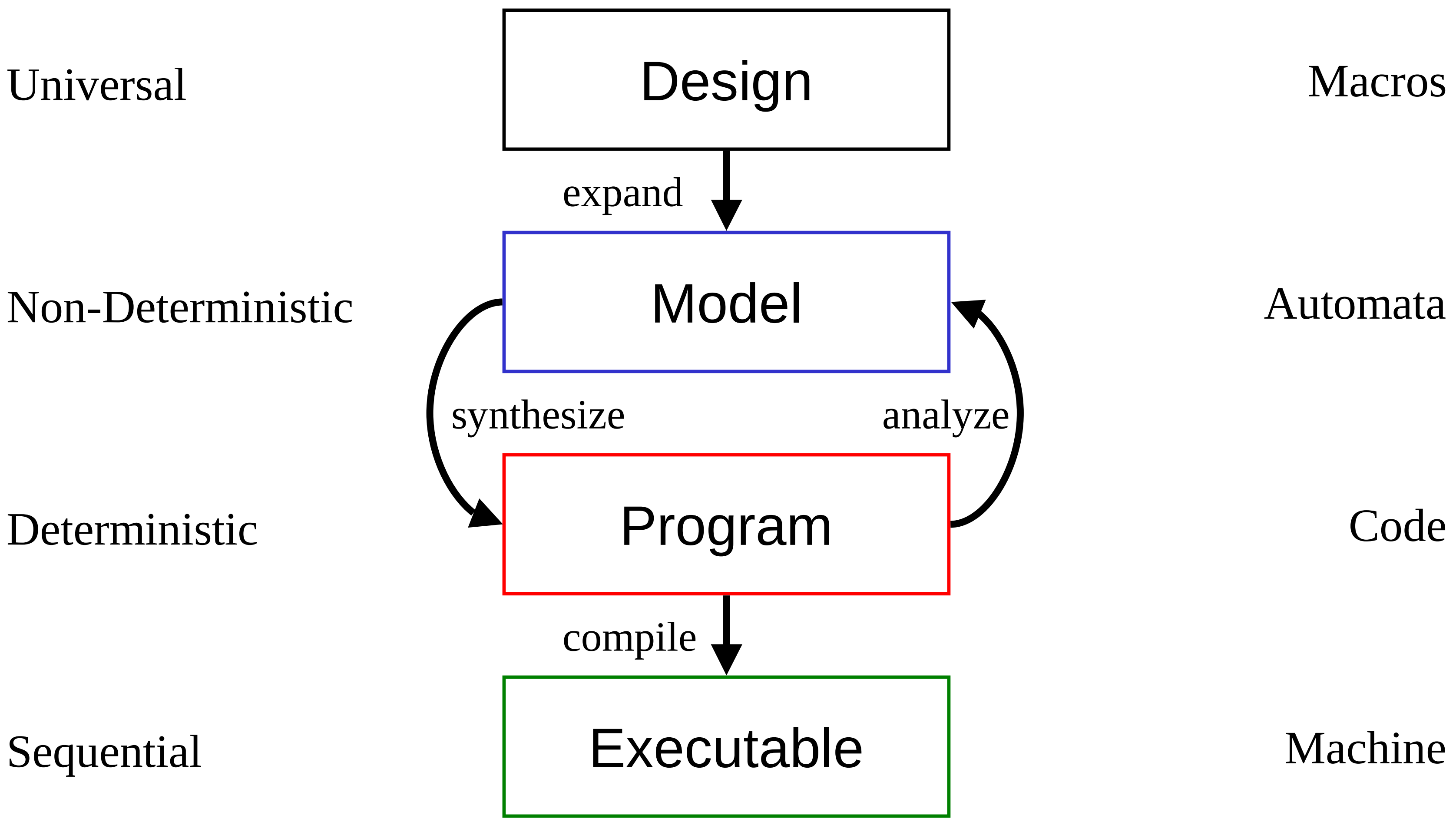
Formal Verification

Property Space

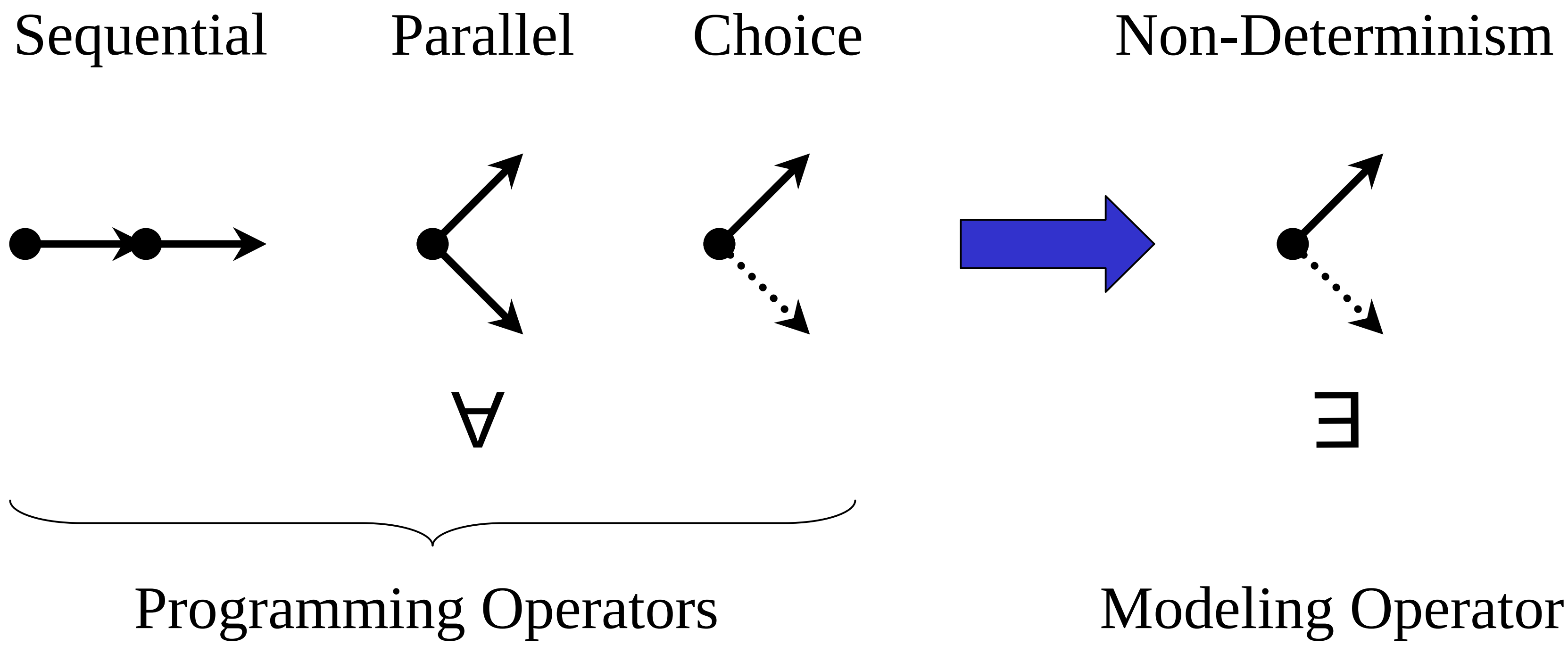


- Safety: Wrong things never happen!
- Liveness: Something useful will happen eventually!

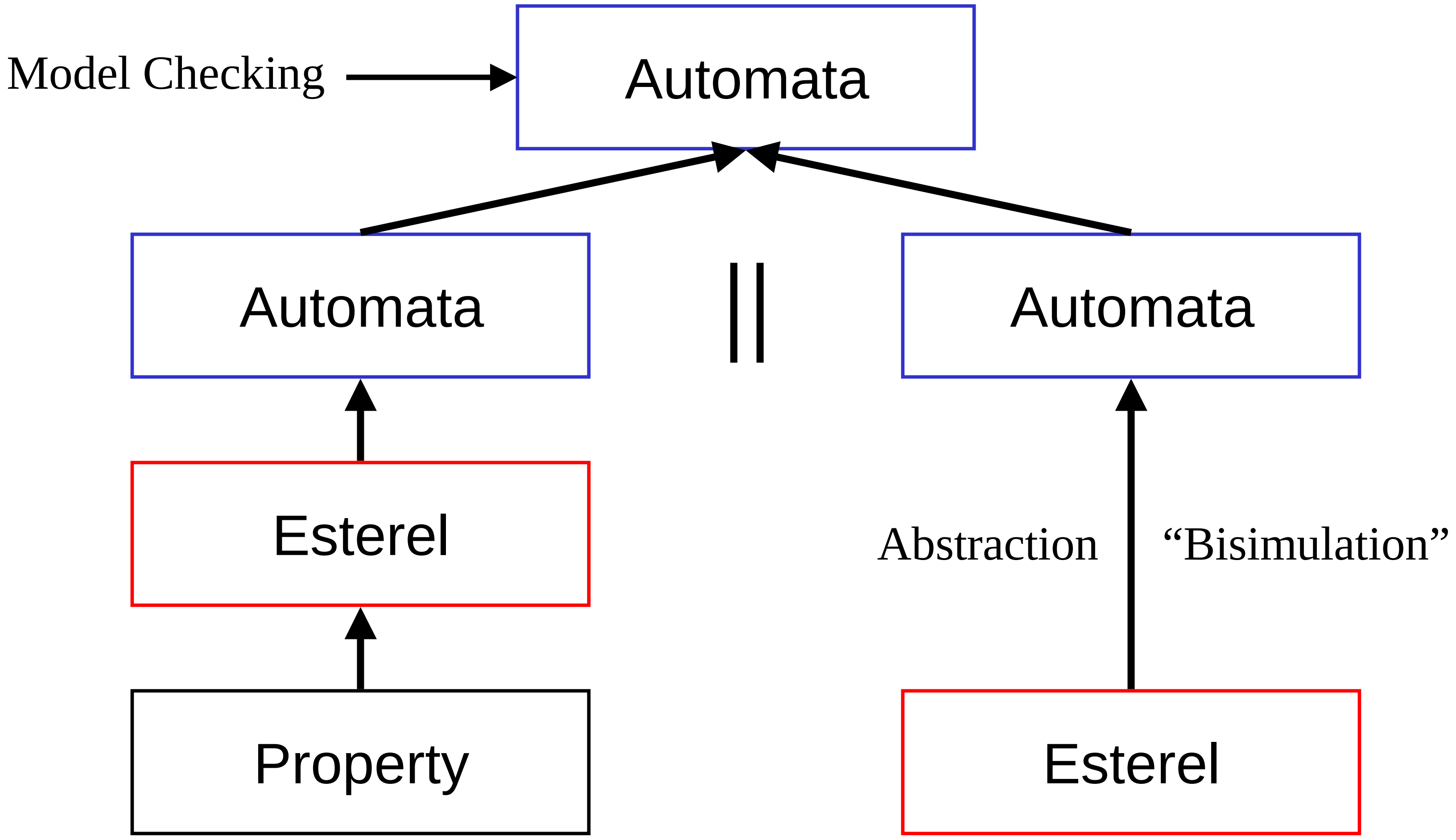
Language Hierarchy



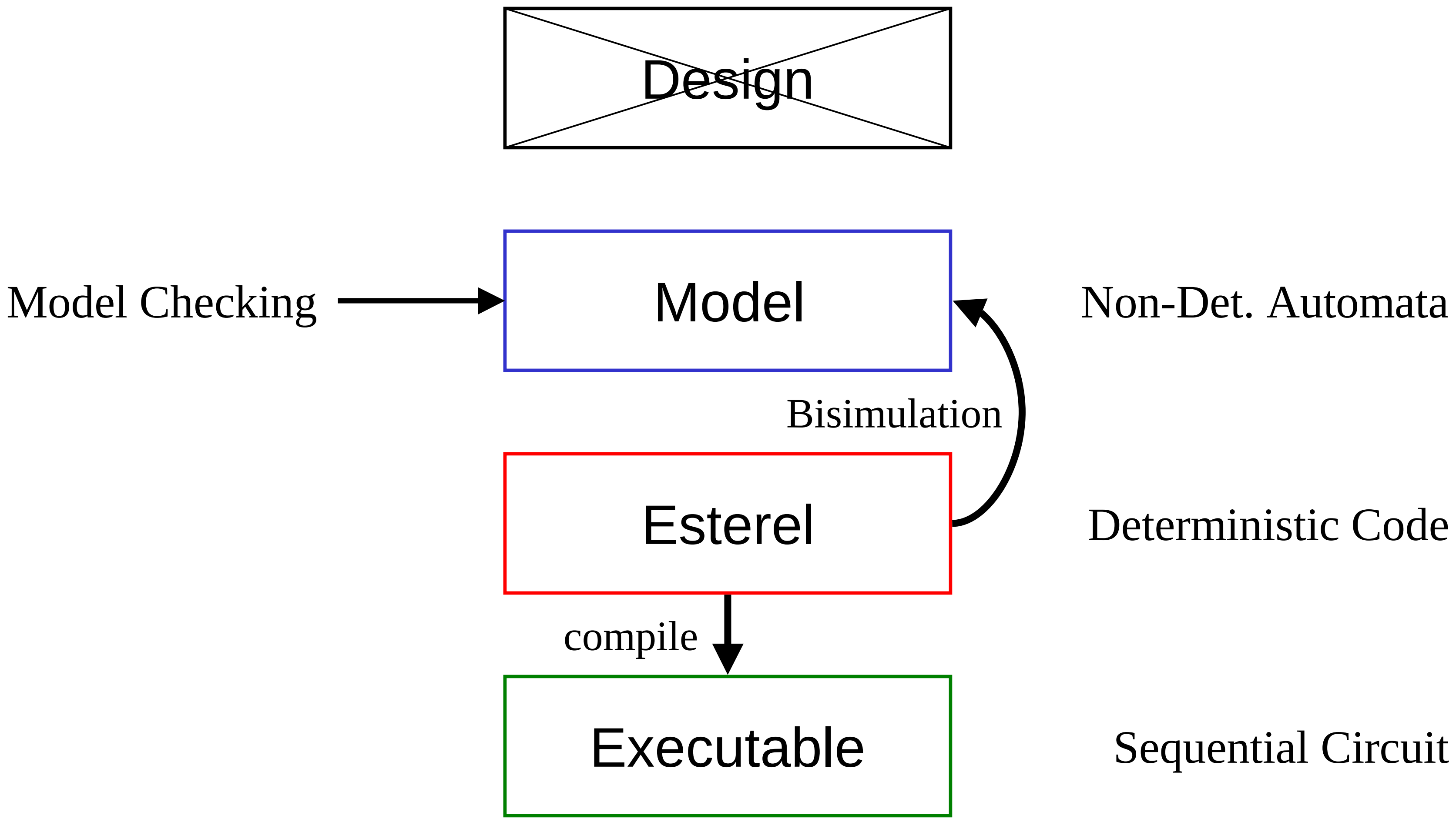
Non-Determinism



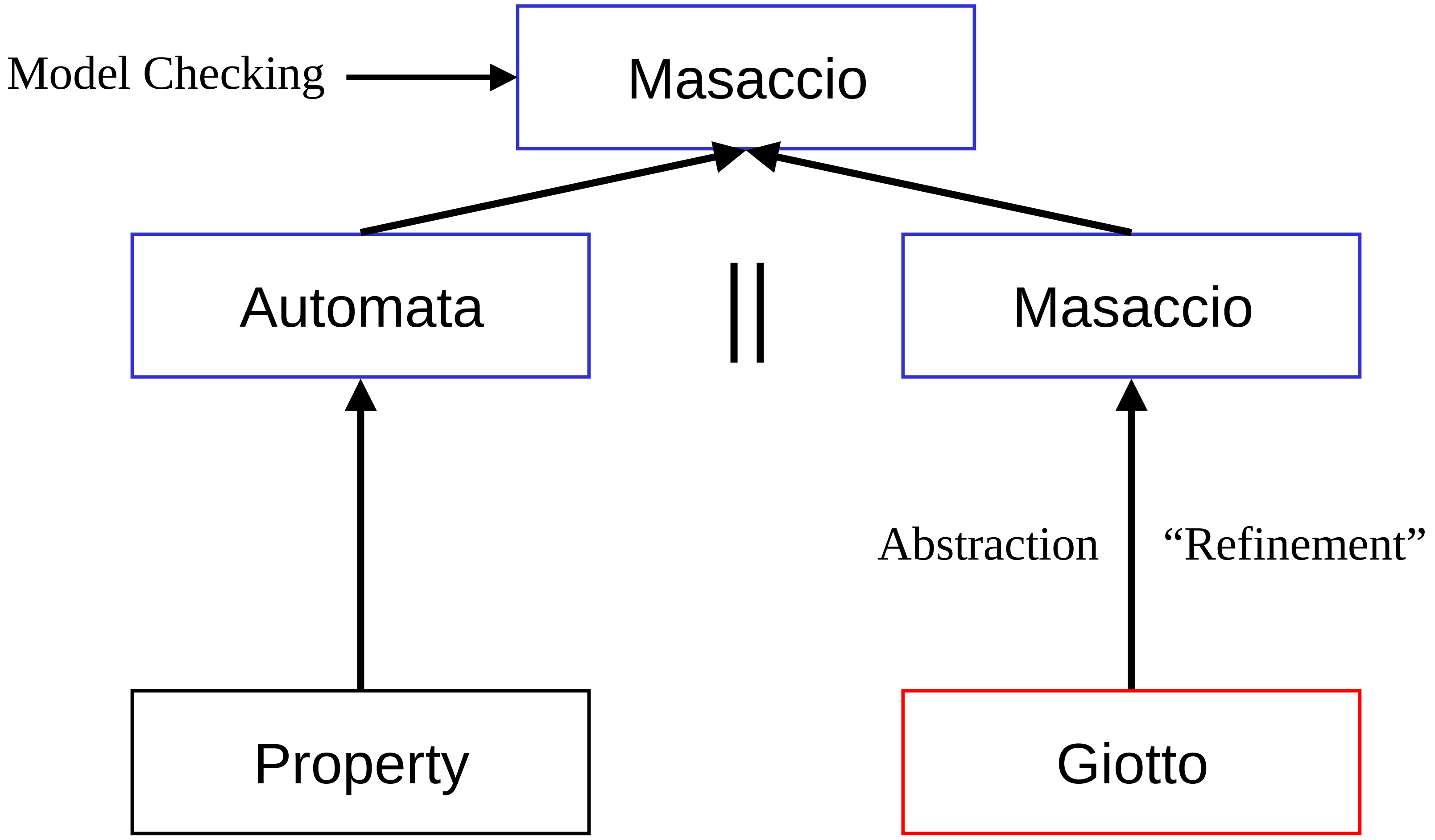
Esterel: Verification



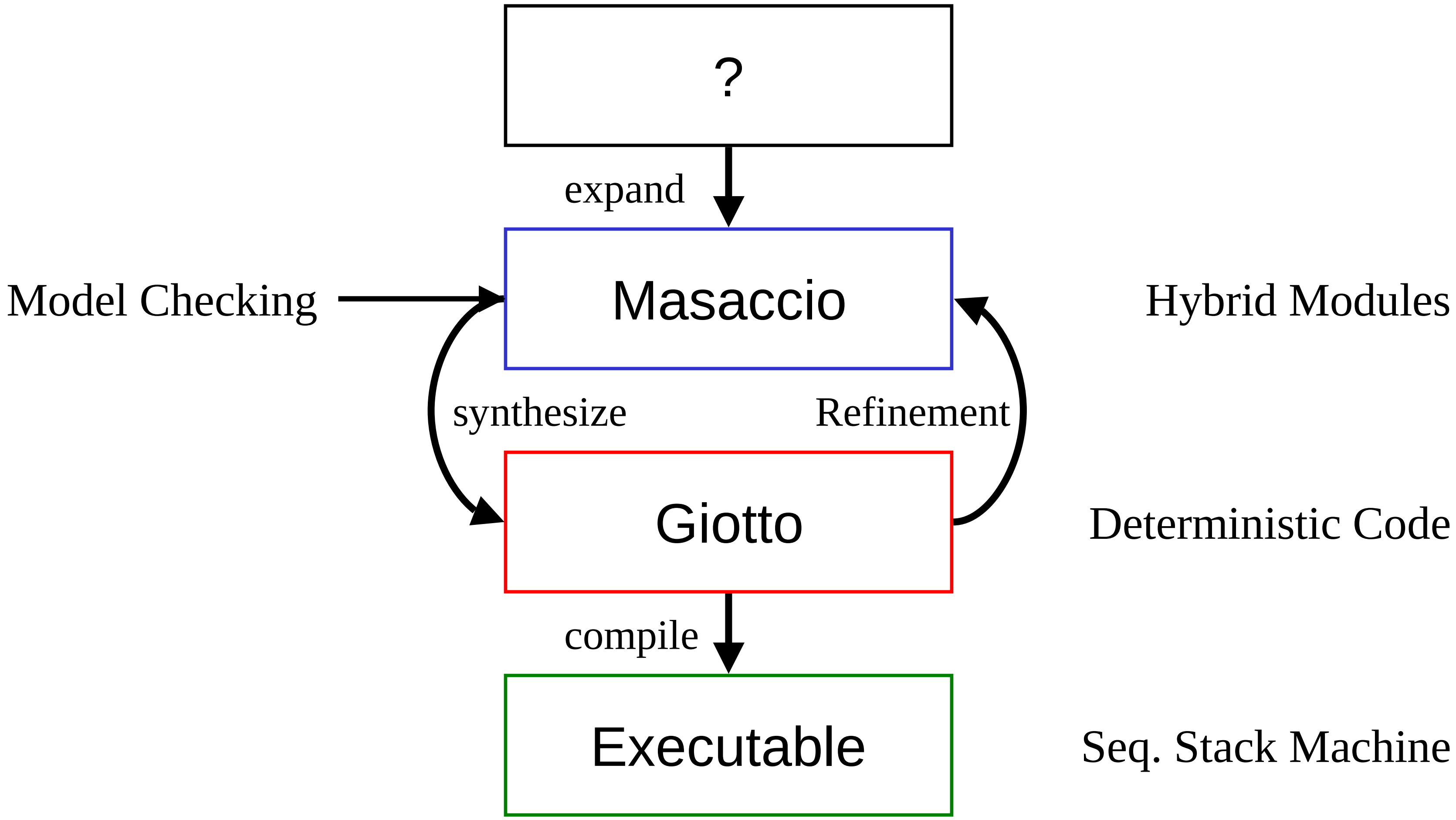
Esterel: Hierarchy



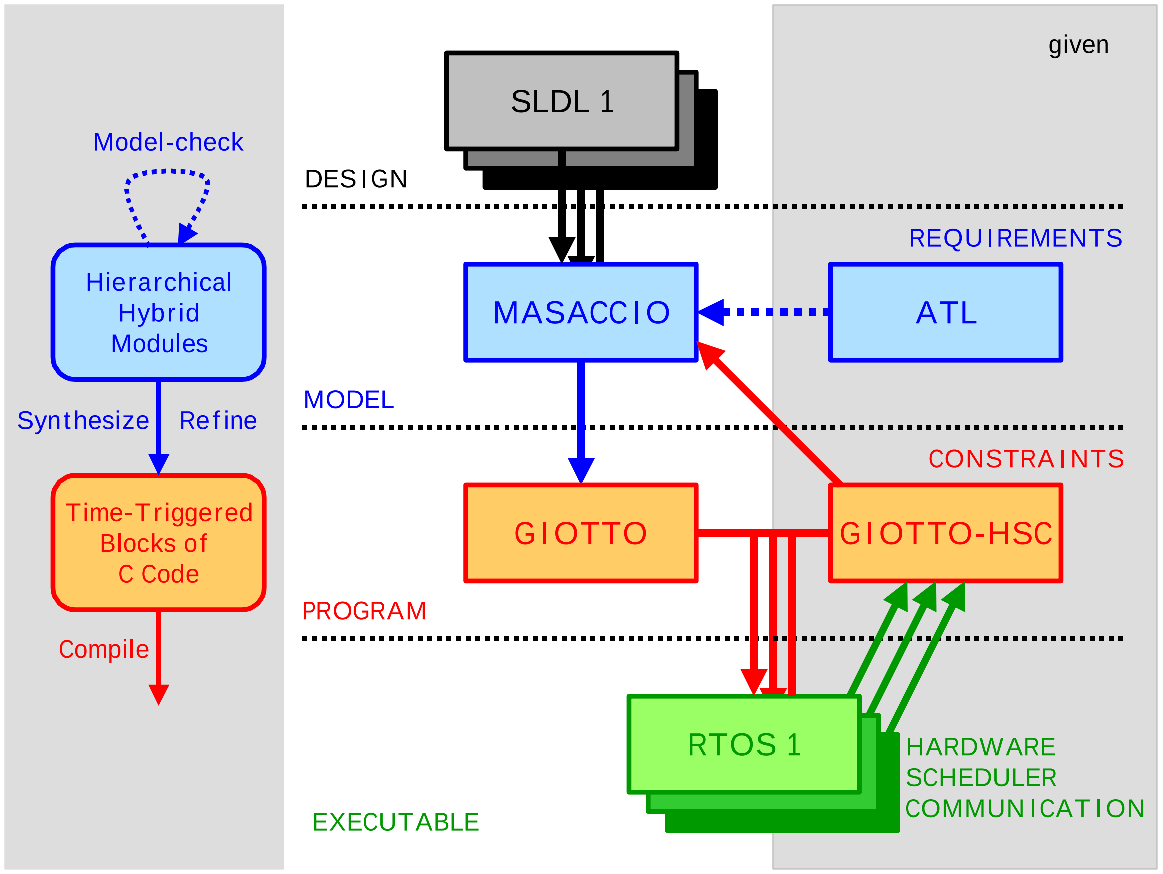
Giotto: Verification



Giotto: Hierarchy



Giotto: Hierarchy



Literature

- Esterel:
  - Papers @ www.esterel.org
- Giotto:
  - T.A. Henzinger. Masaccio: A Formal Model for Embedded Components. LNCS 1872, Springer, 2000, pp. 549-563.

End