Towards Run-Time Verification for Real-Time Safety-Critical Systems

Geoffrey Nelissen

Systems Do not Get Simpler

- Every day, computing platforms become more and more complex
  - Unicore → Multicore → Manycore
  - Apparition of buses, then NoCs
  - Shared memory and shared caches
  - Complex cache replacement policies
  - …
- Software becomes more complex too
  - Parallel and/or distributed tasks
  - Execution affinities (➔ migrations)
  - …

➔Difficult to model, analyse and verify

Systems Do not Get Simpler

- Yet, safety critical systems would like to adopt those new architectures
  - For their performances
  - To reduce costs
  - For availability reasons
  - …

➔ One must prove that all the system requirements are respected

Two Types of Properties to Verify

- Functional properties
- Extra-functional properties

Two Types of Properties to Verify

- Functional properties
  - Everything that relate to the result produced or the order of execution
  - Examples:
    - A must execute before B
    - If A executes than B must eventually execute
    - C cannot execute between A and B
    - The result returned by A must be positive
    - The sensor readings cannot be smaller than 3
- Extra-functional properties

Two Types of Properties to Verify

- Functional properties
- Extra-functional properties

Two Types of Properties to Verify

- Functional properties
- Extra-functional properties
  - Everything that does not relate to the result produced or the order of execution
  - Examples:
    - A must complete within 10ms
    - A cannot execute for more than 5ms
    - B must execute at last 10ms after A
    - Core temperature must remain under 60°C
    - Power consumption must remain under 5W
  - In this work, we limit ourselves to timing properties

Static Verification is Usually Impractical

- For functional properties
  - Time and complexity to actually prove something
  - Explosion of possible states
  - Theoretical limitations of the models
- For extra-functional properties
  - most data are available only at run-time

Modeling and Analysis are Based on Assumptions

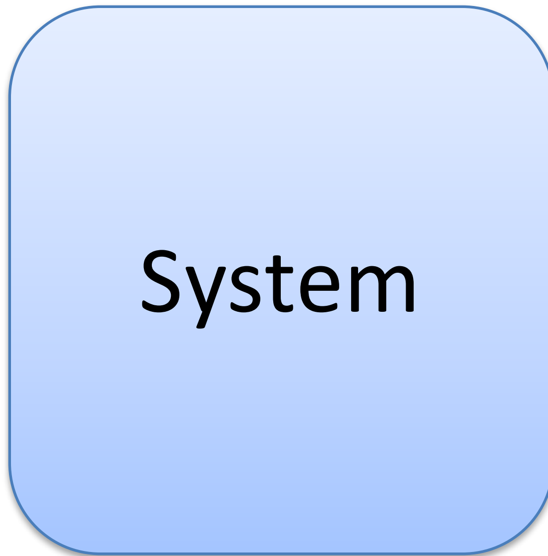
- For instance, in real-time scheduling theory:
  - Execution time never exceeds the WCET
  - The minimum inter-arrival time is lower bounded by T_i
  - The jitter is upper bounded by J_i
  - …

➔ Nothing proves that they are actually respected at run-time

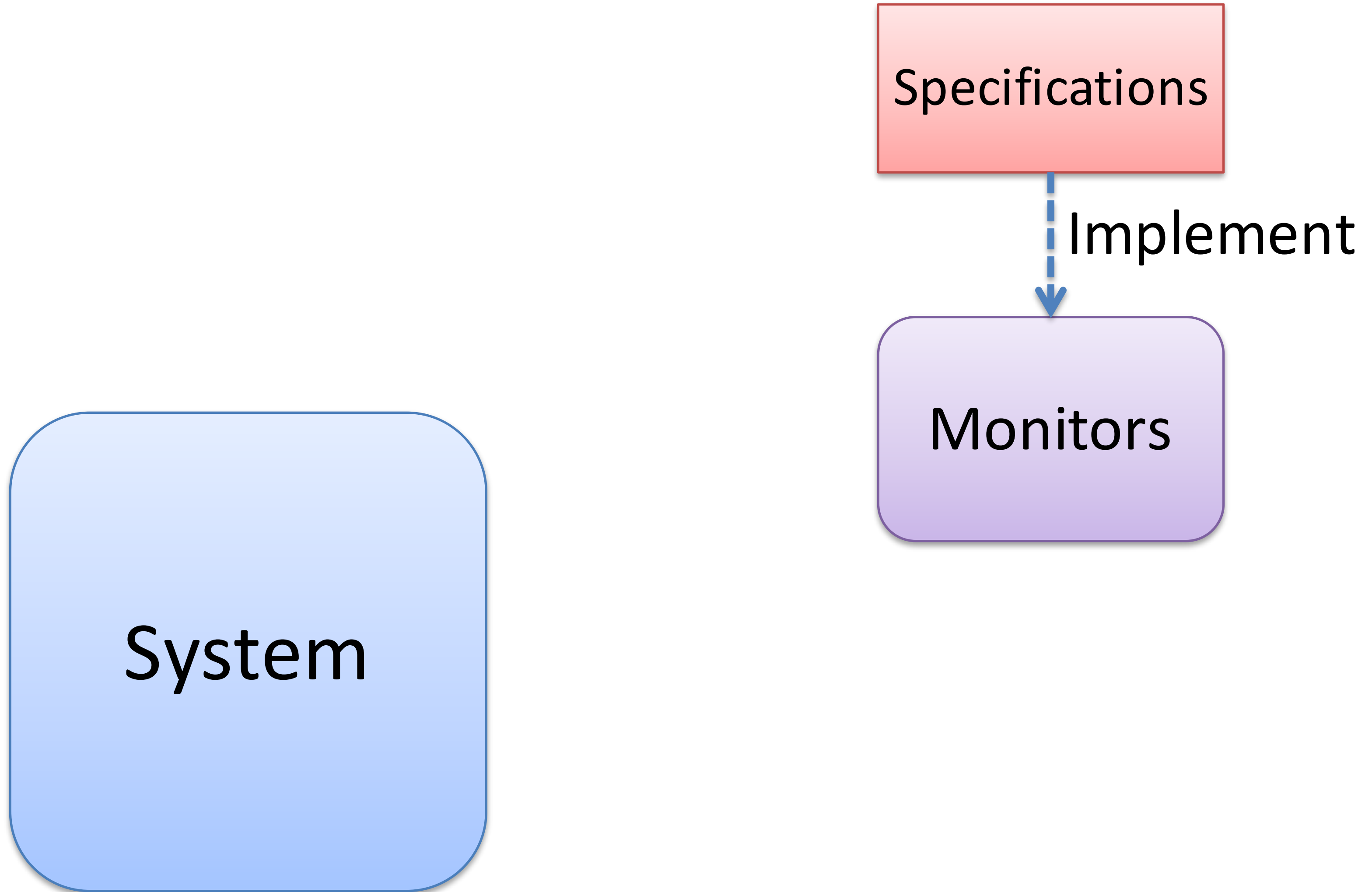
➔ Testing is used to increase the confidence but does not cover all cases

RUN-TIME VERIFICATION: BASIC CONCEPTS

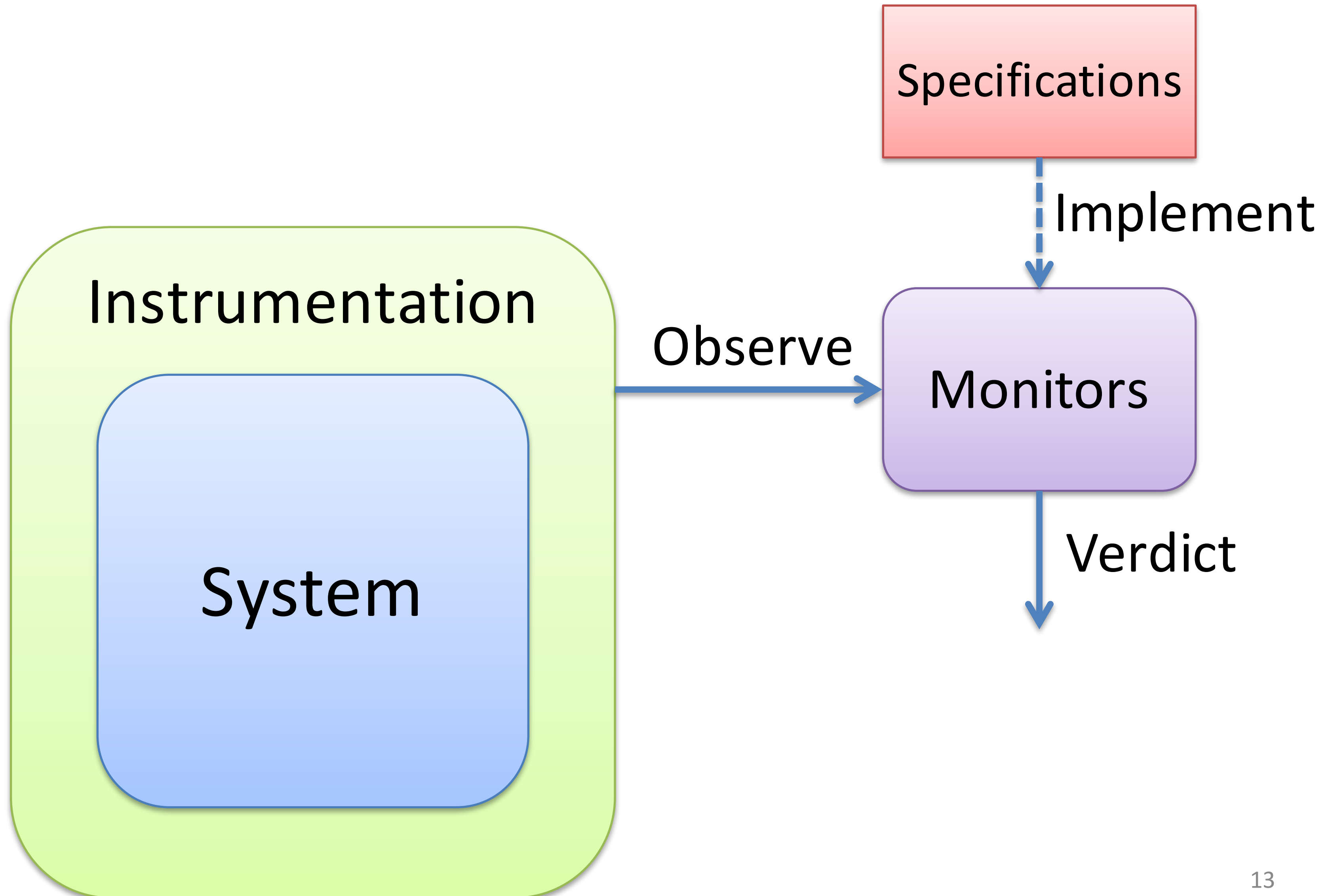
Run-time verification



Run-time verification



Run-time verification



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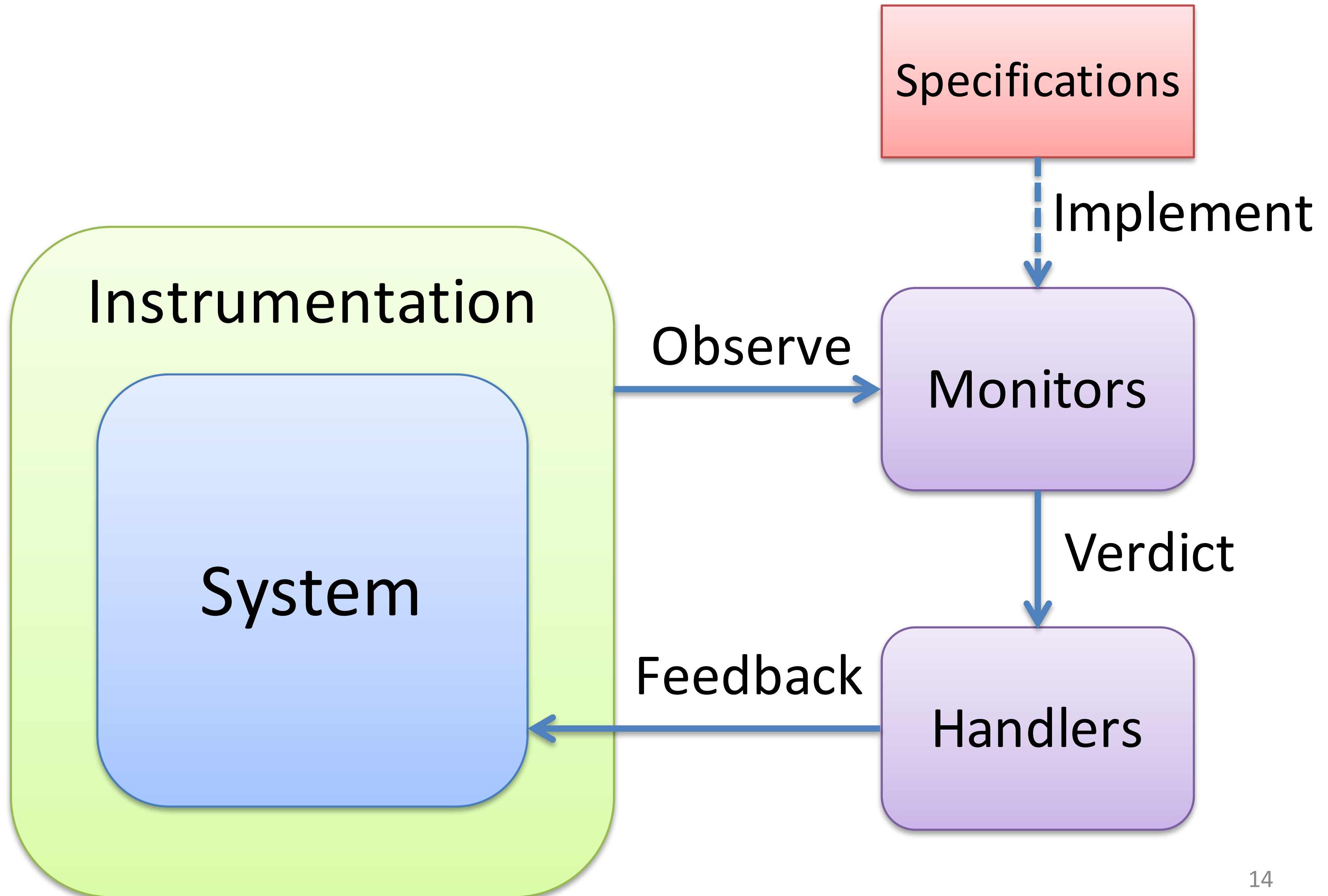

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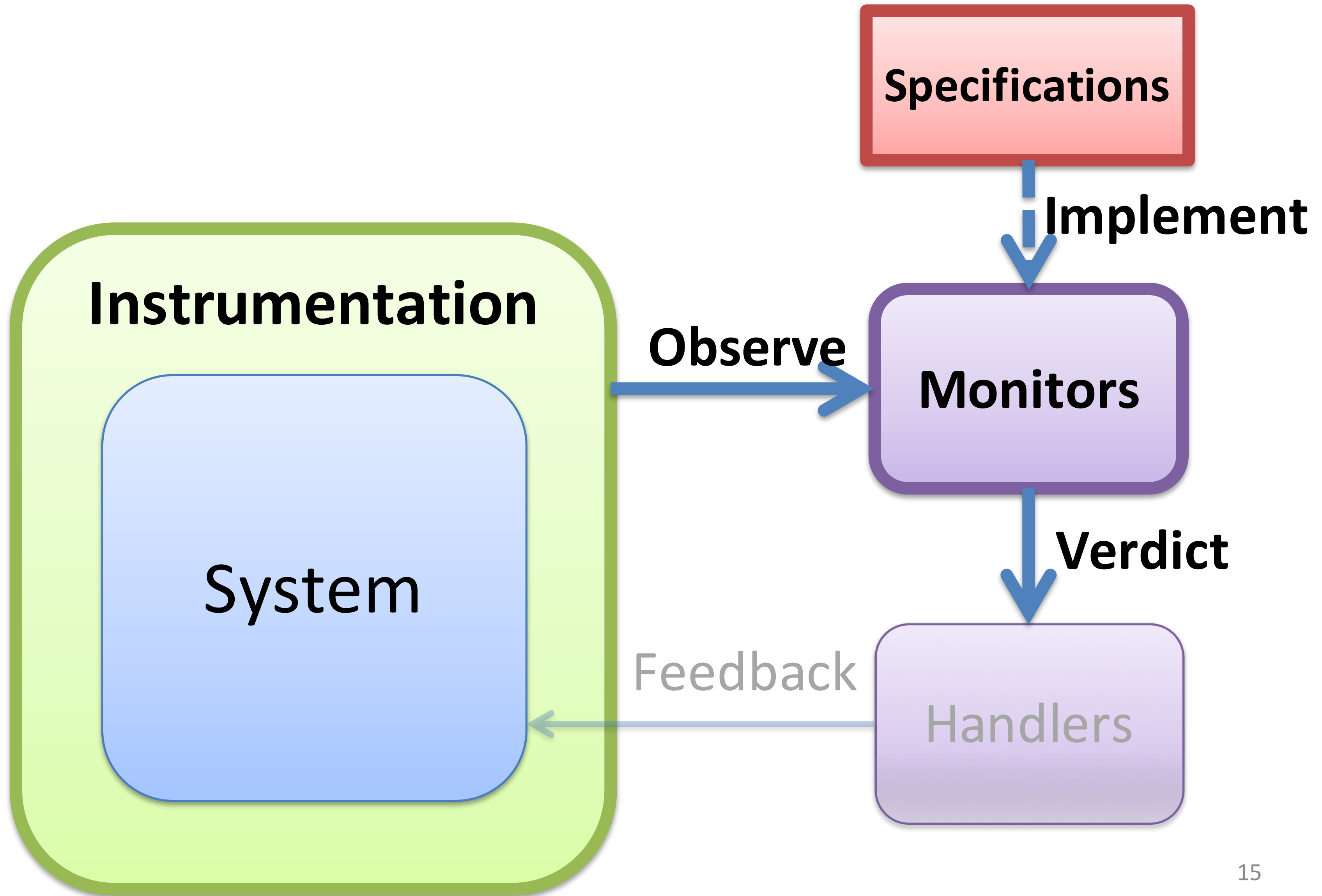
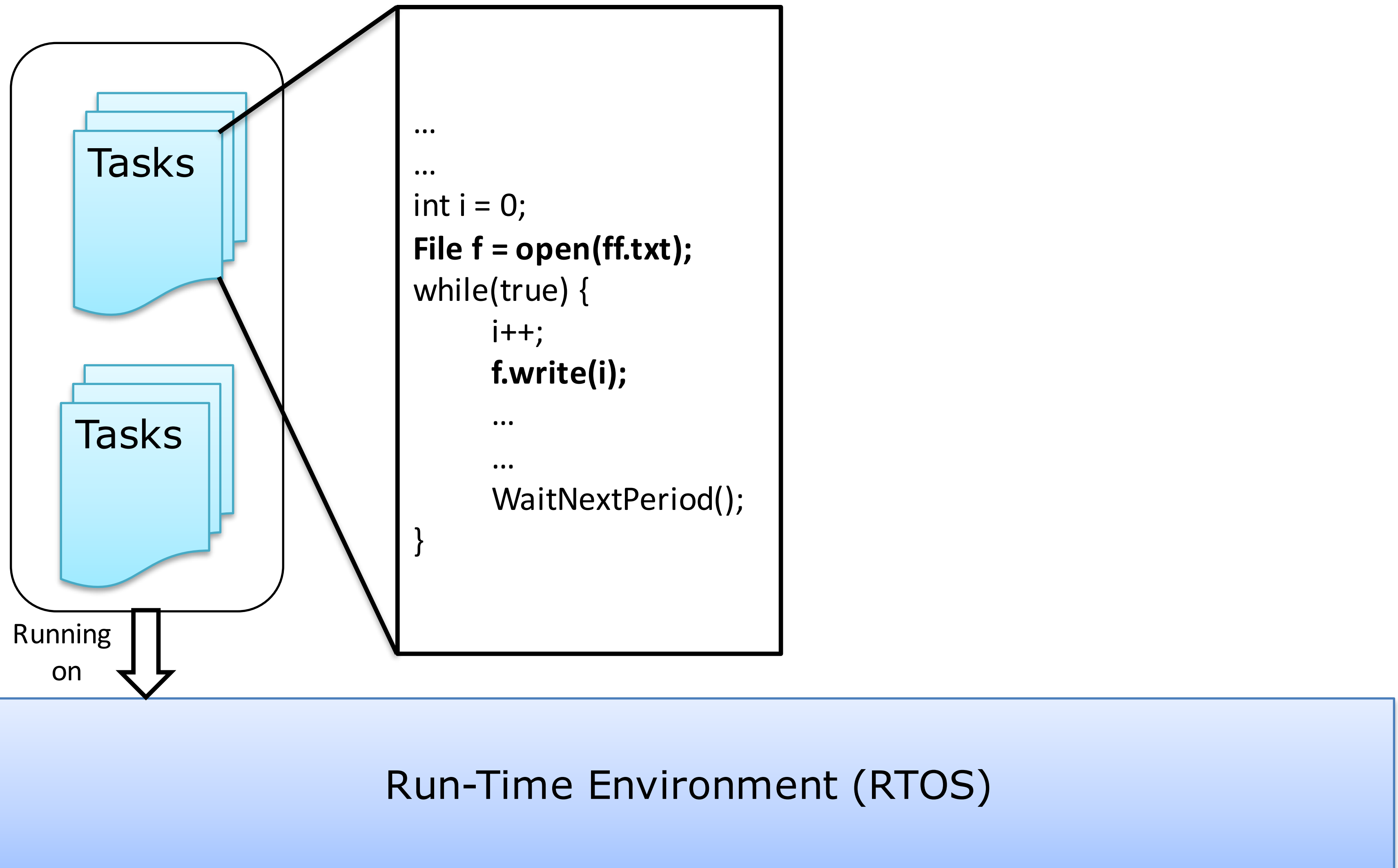


EXAMPLES

Verification of a Functional Property

Verification of a Functional Property



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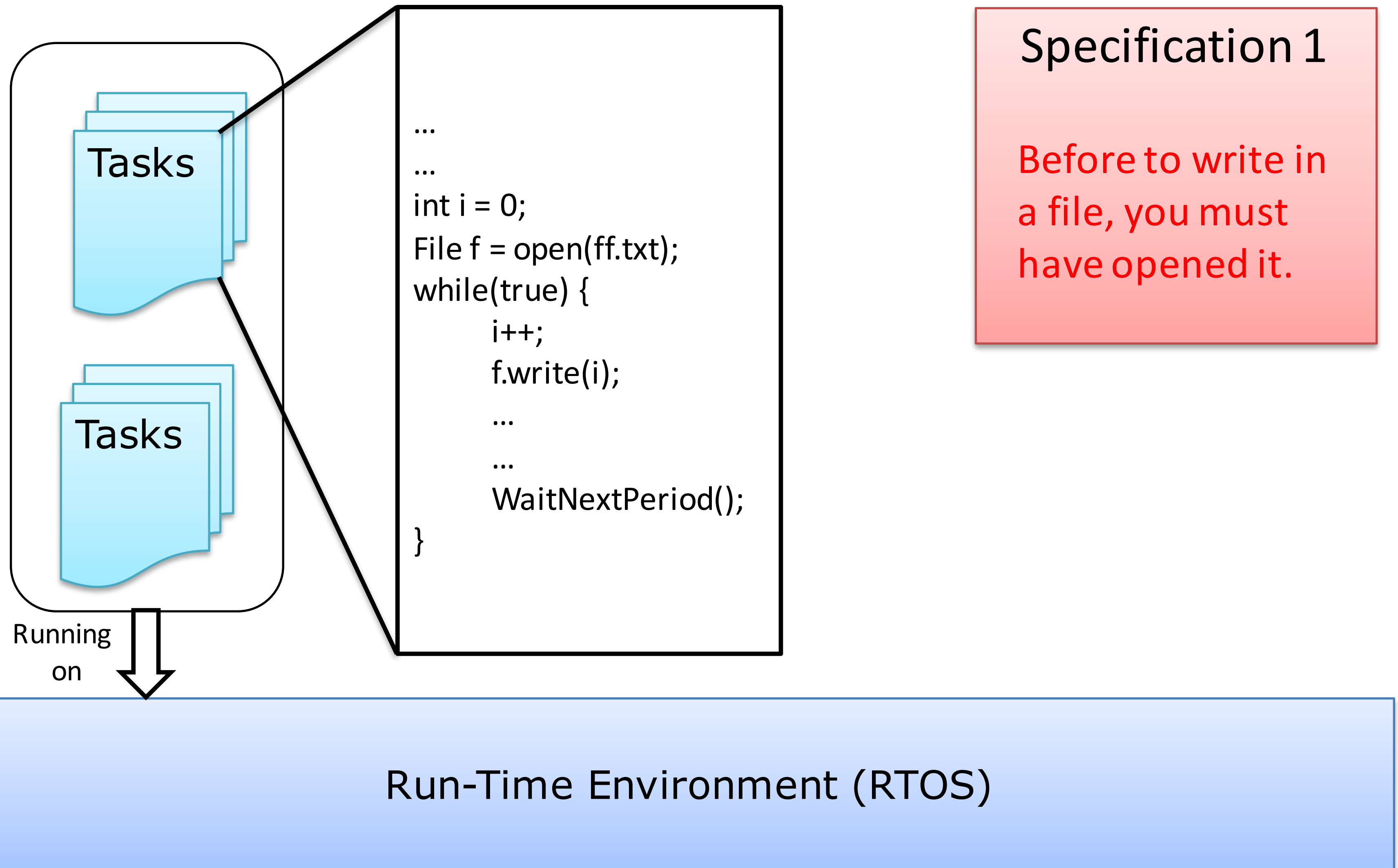

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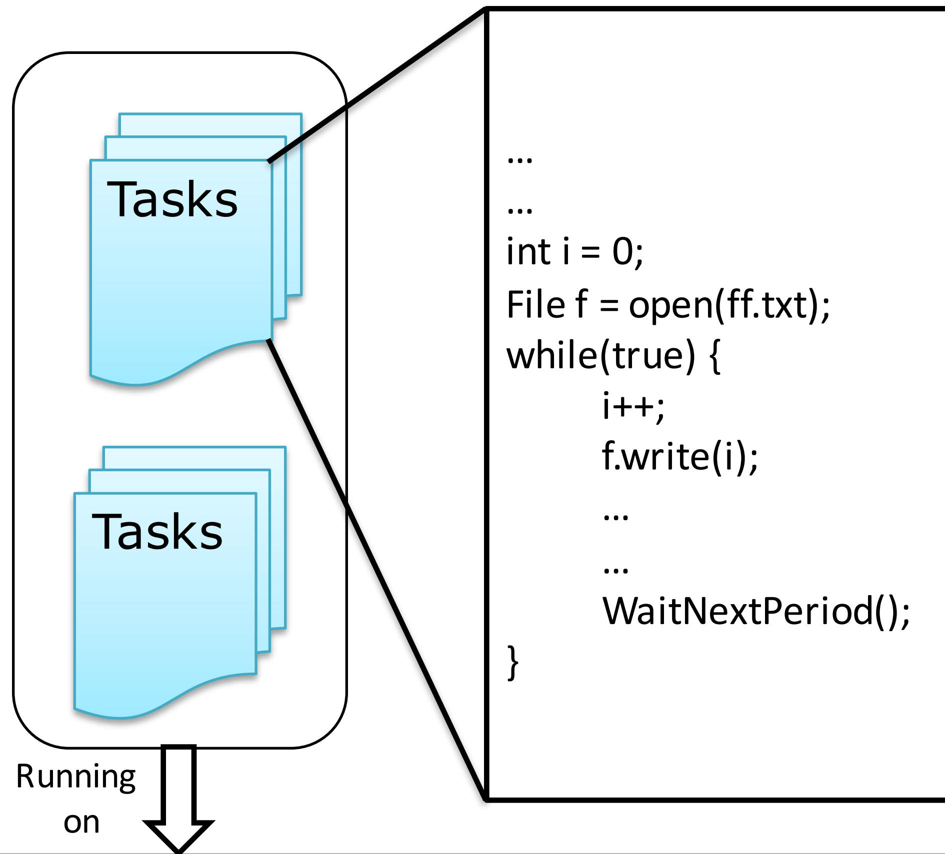
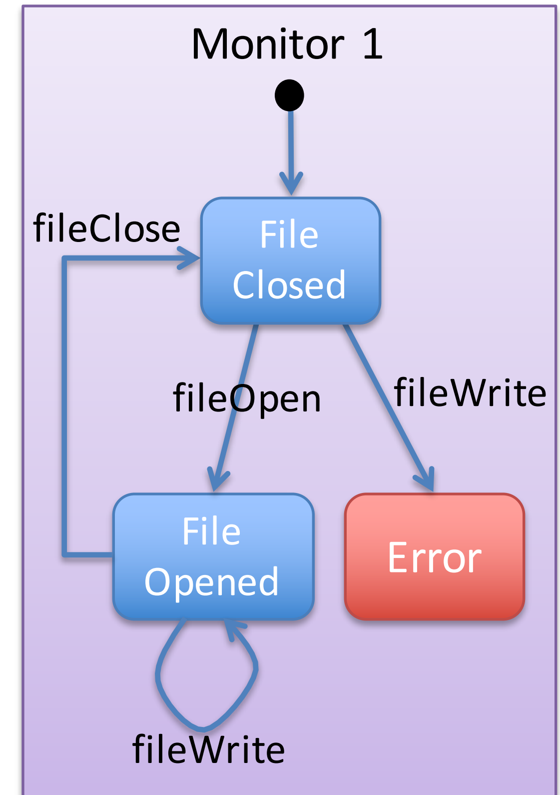
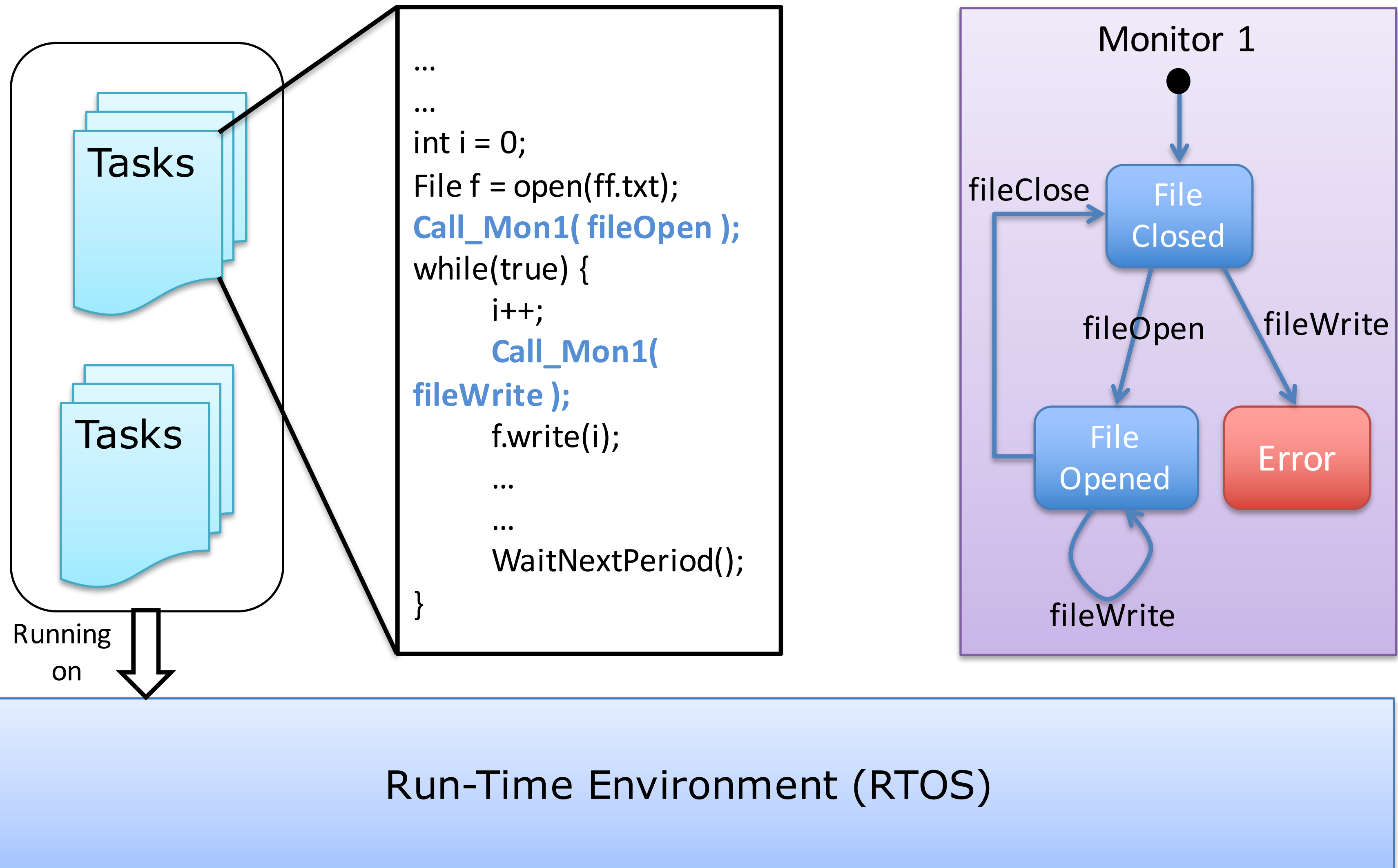




Run-Time Environment (RTOS)

Verification of a Functional Property



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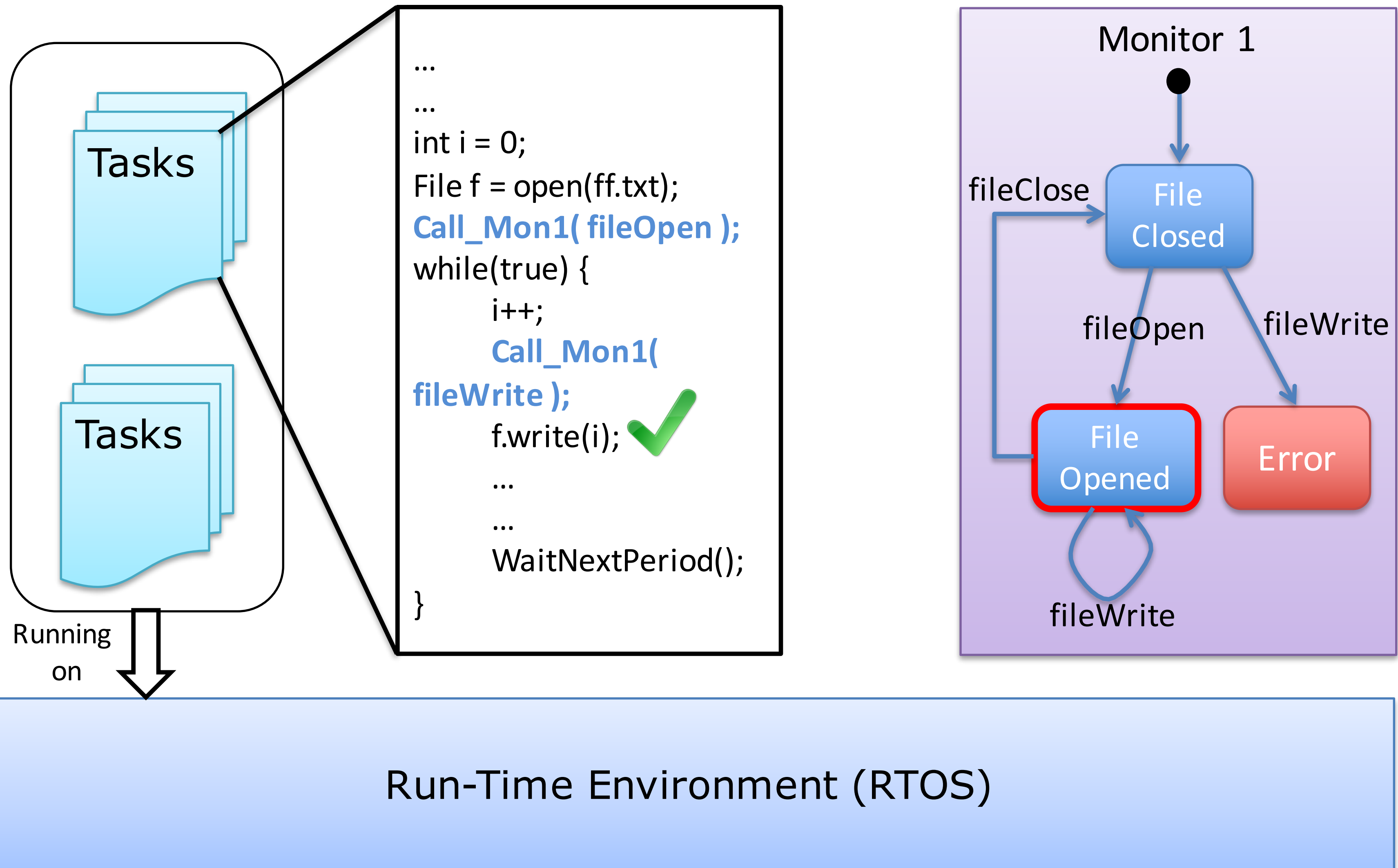

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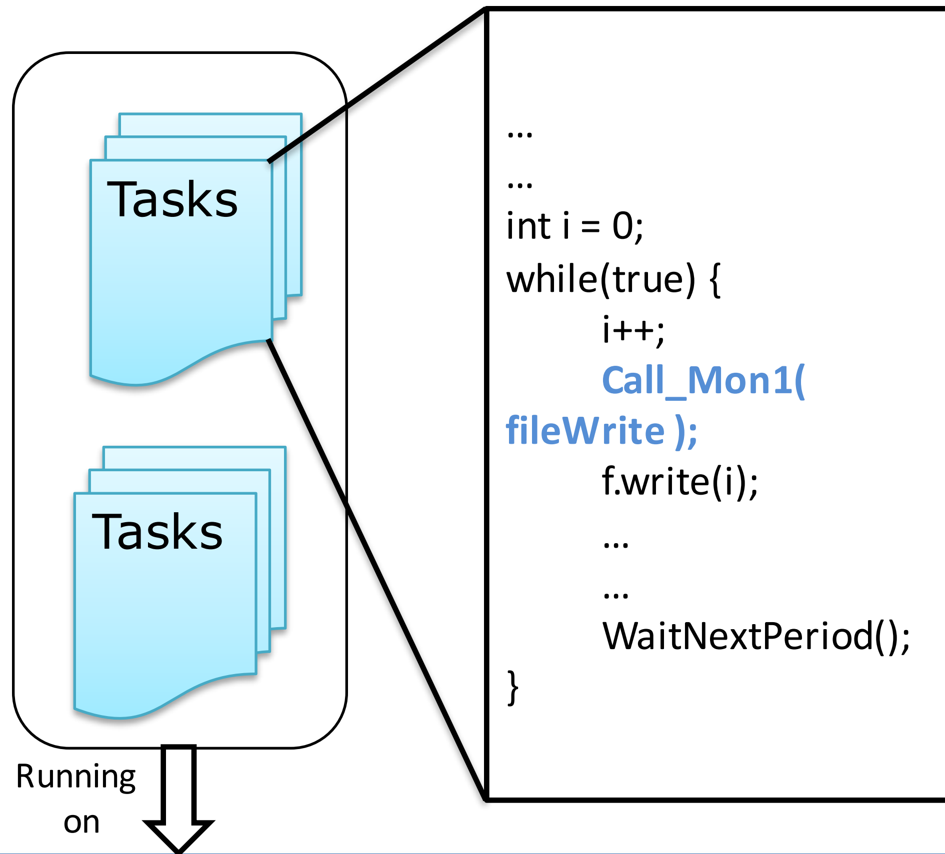

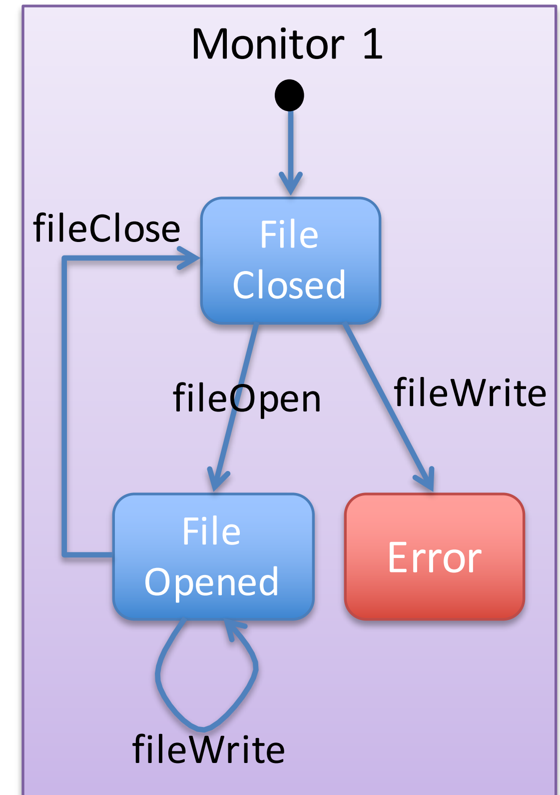

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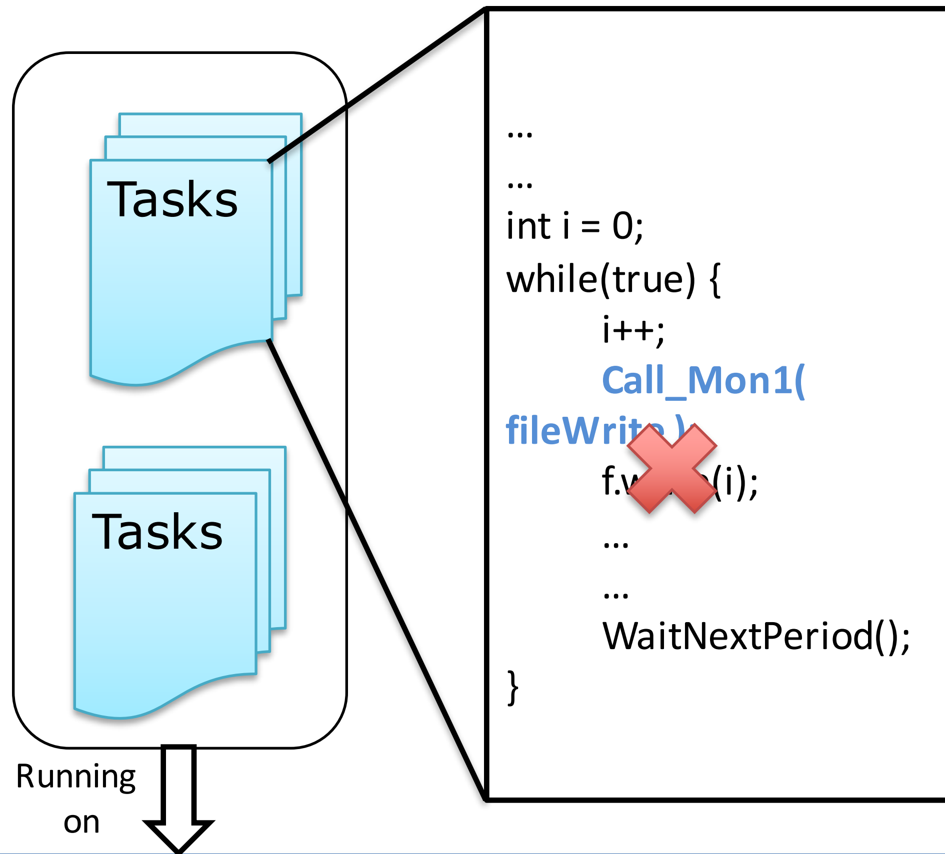
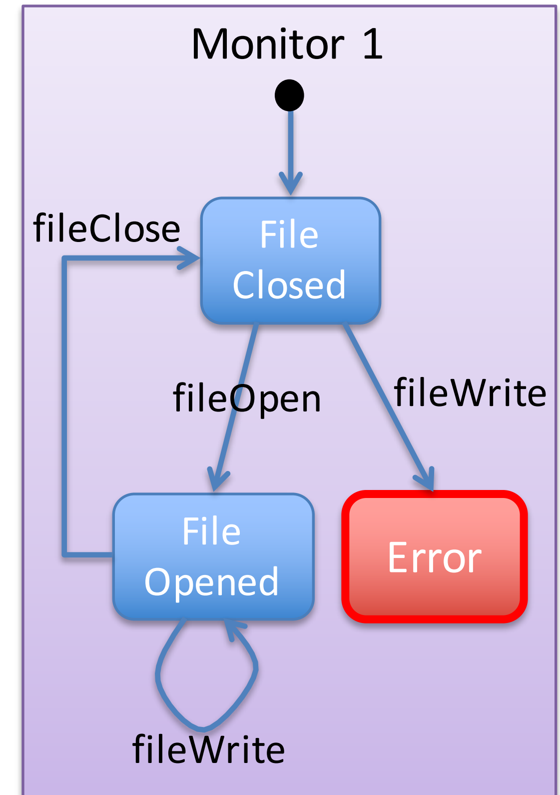
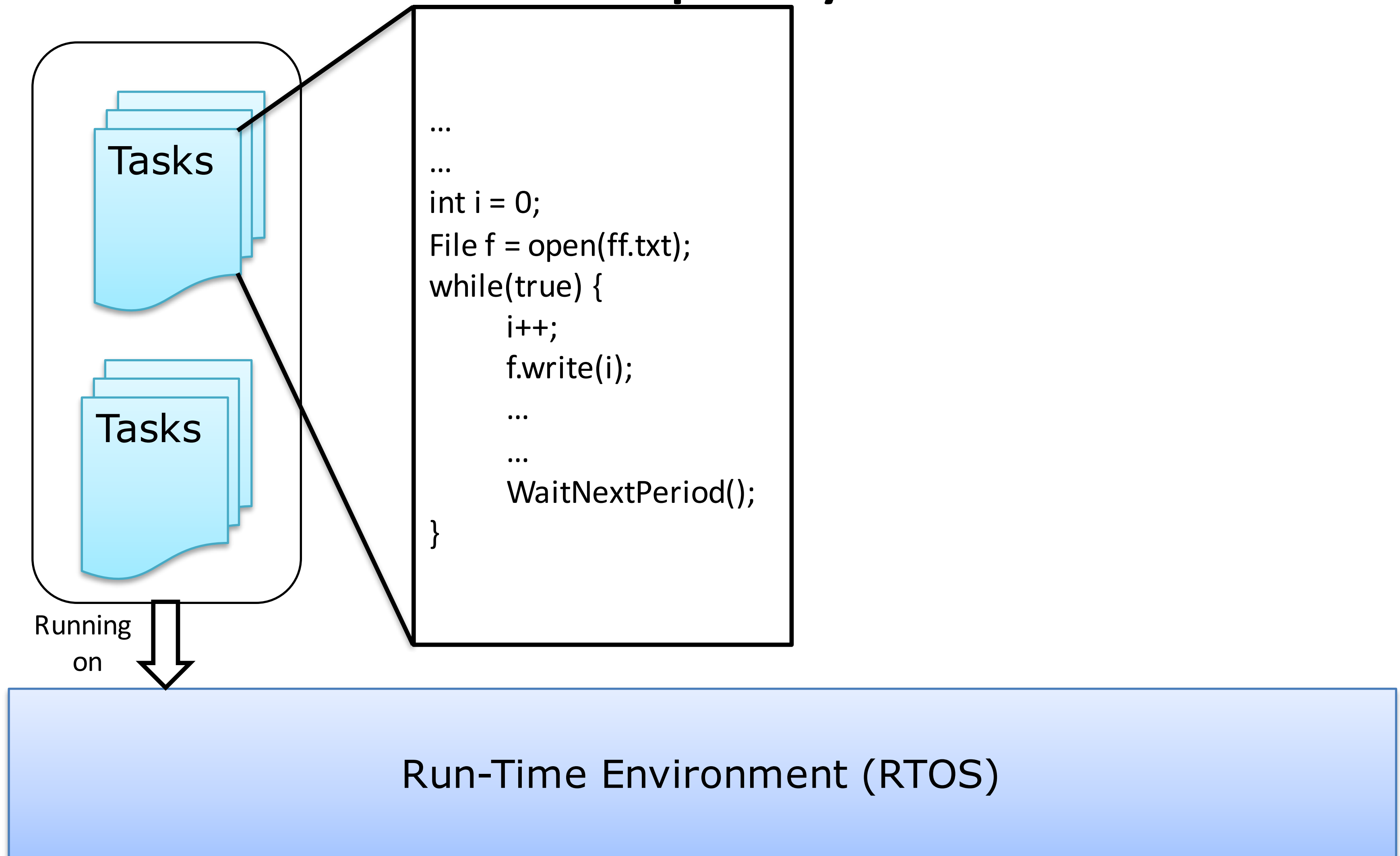


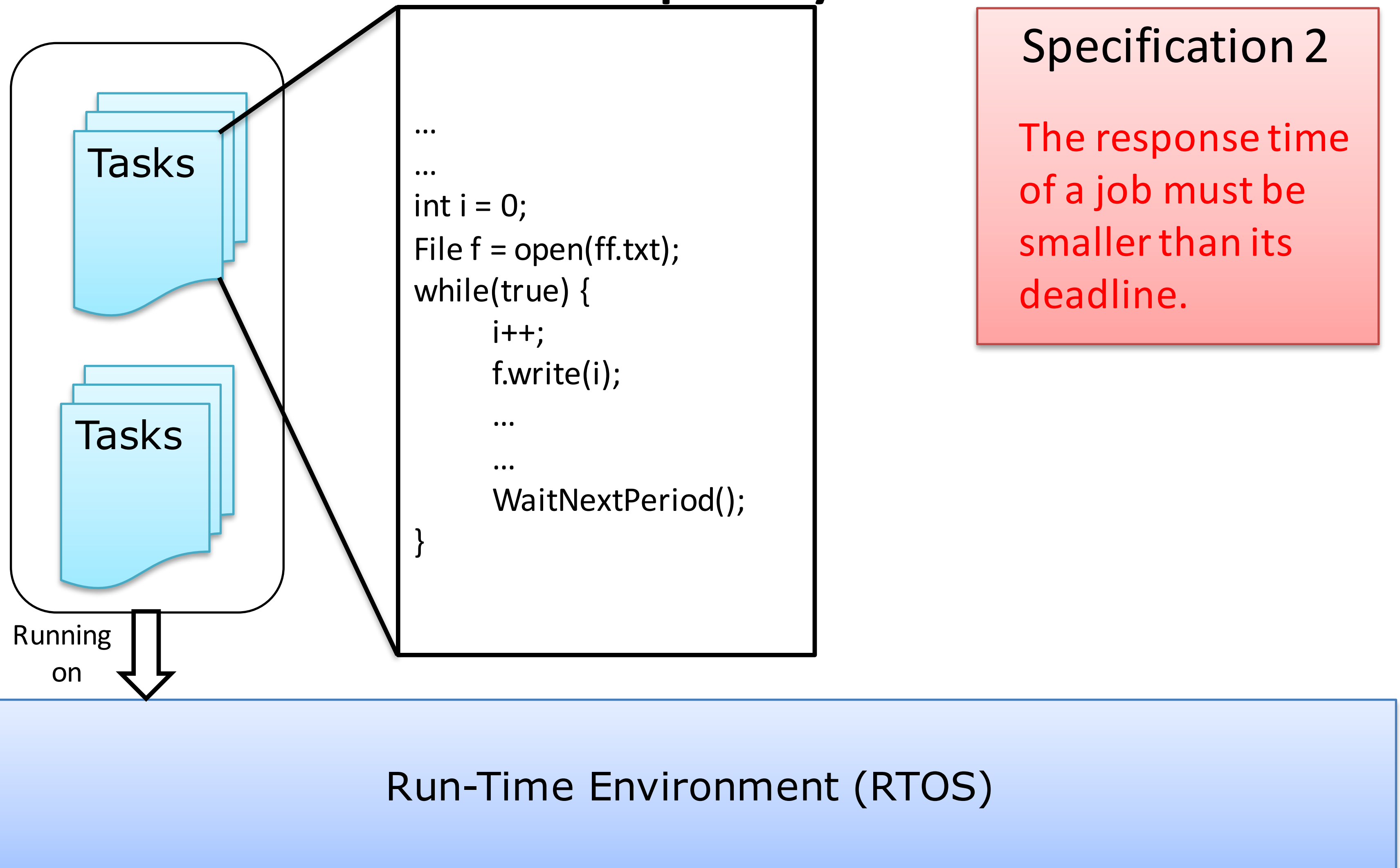


Run-Time Environment (RTOS)

Verification of an Extra-Functional Property



Verification of an Extra-Functional Property



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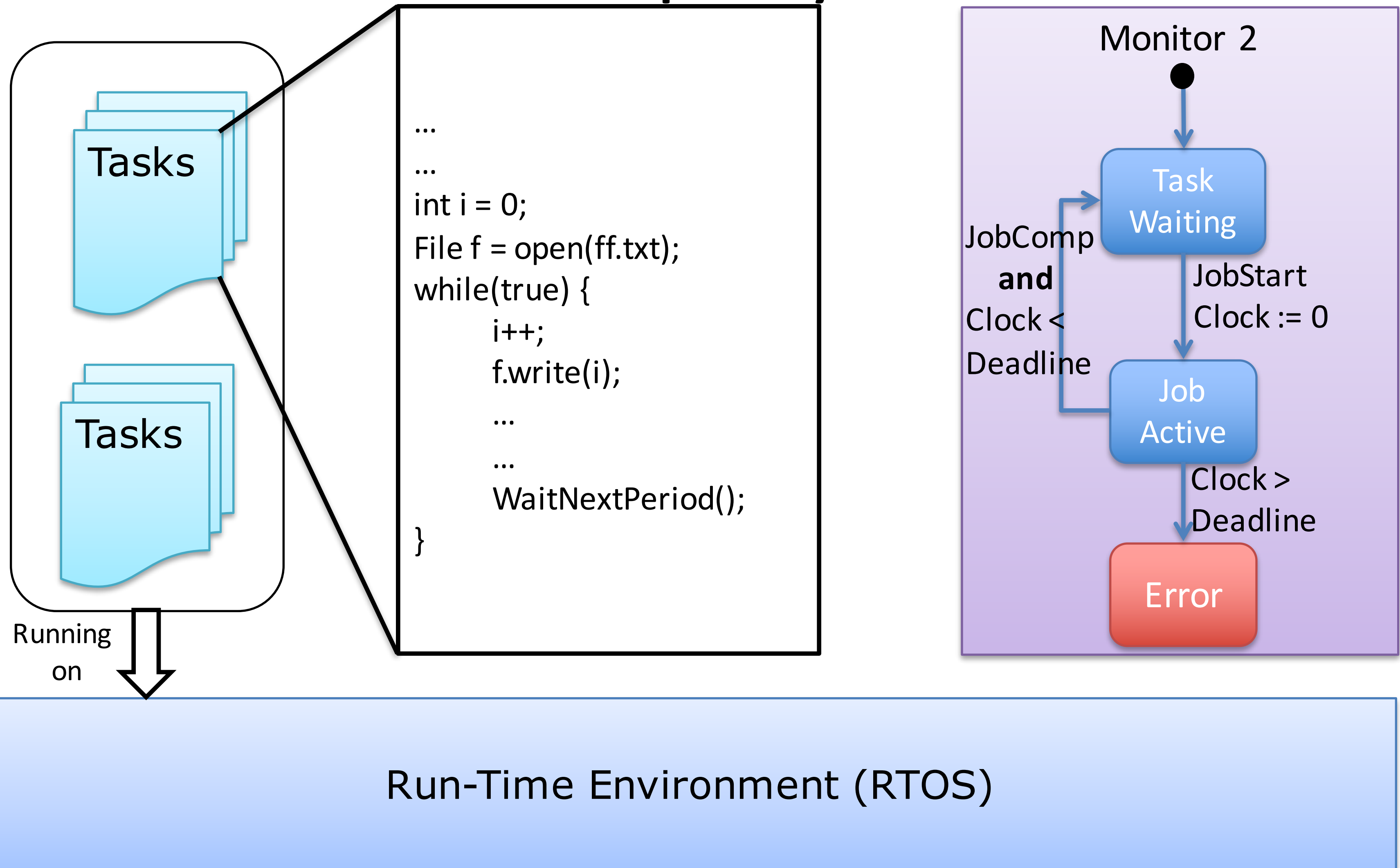

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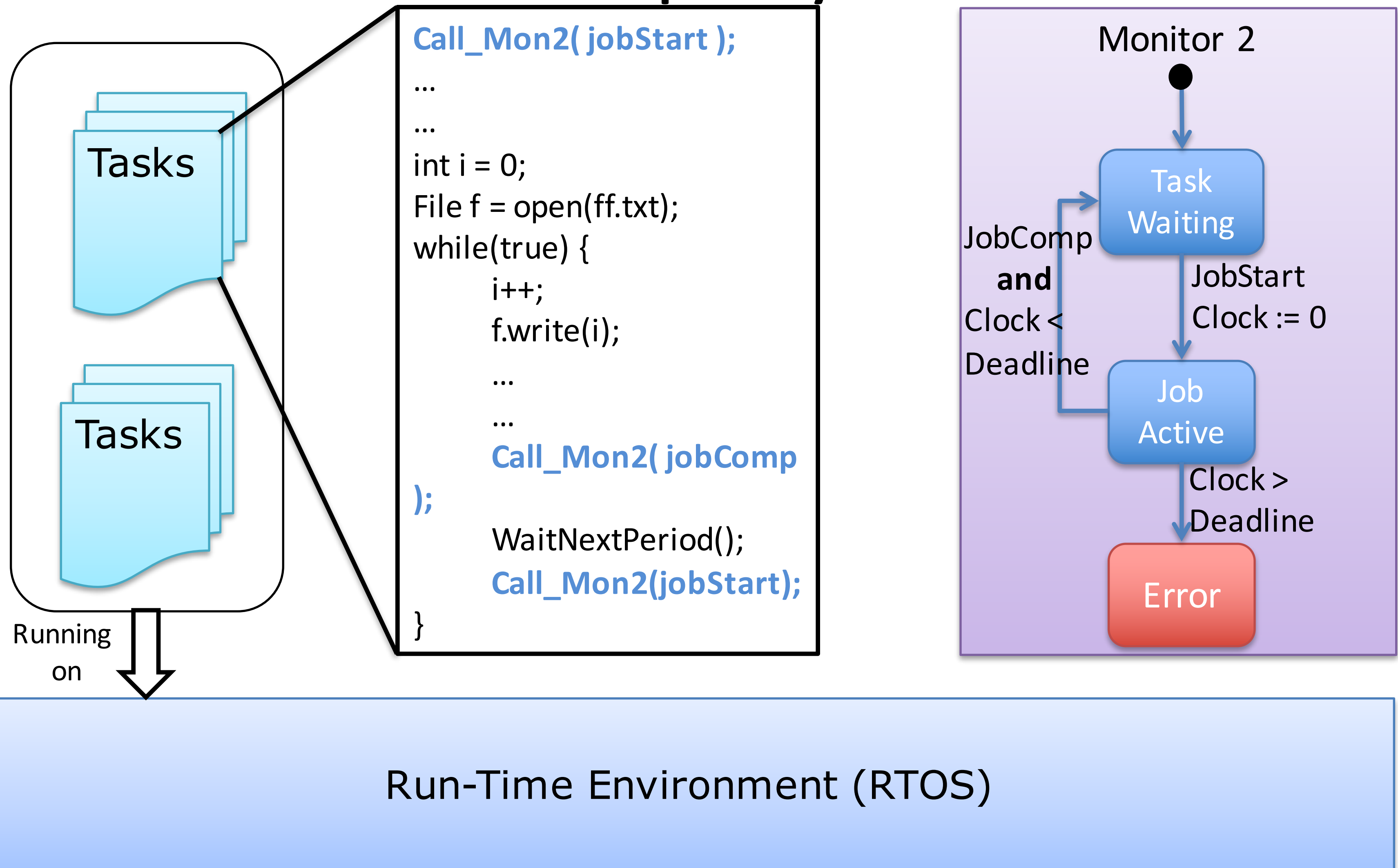
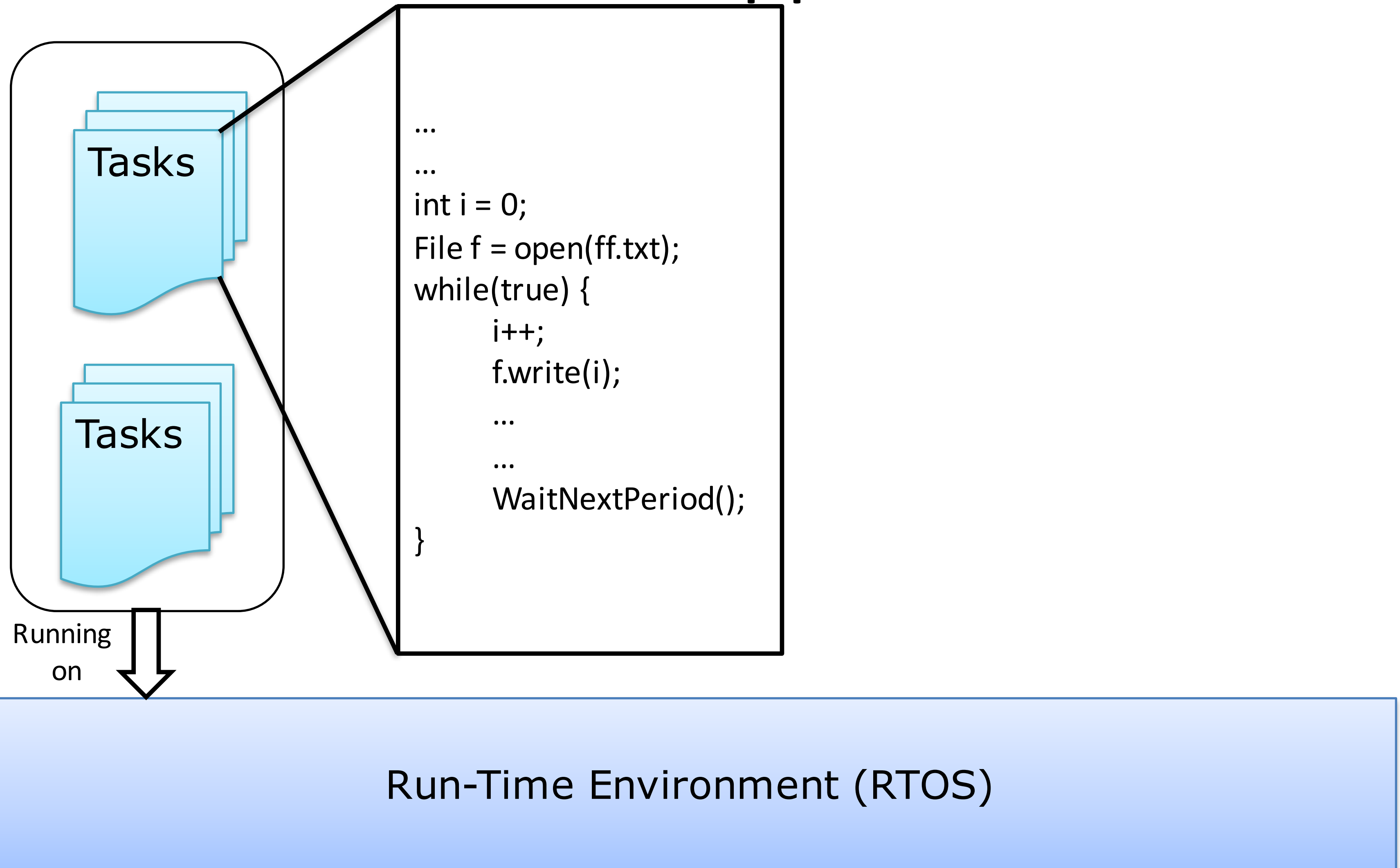
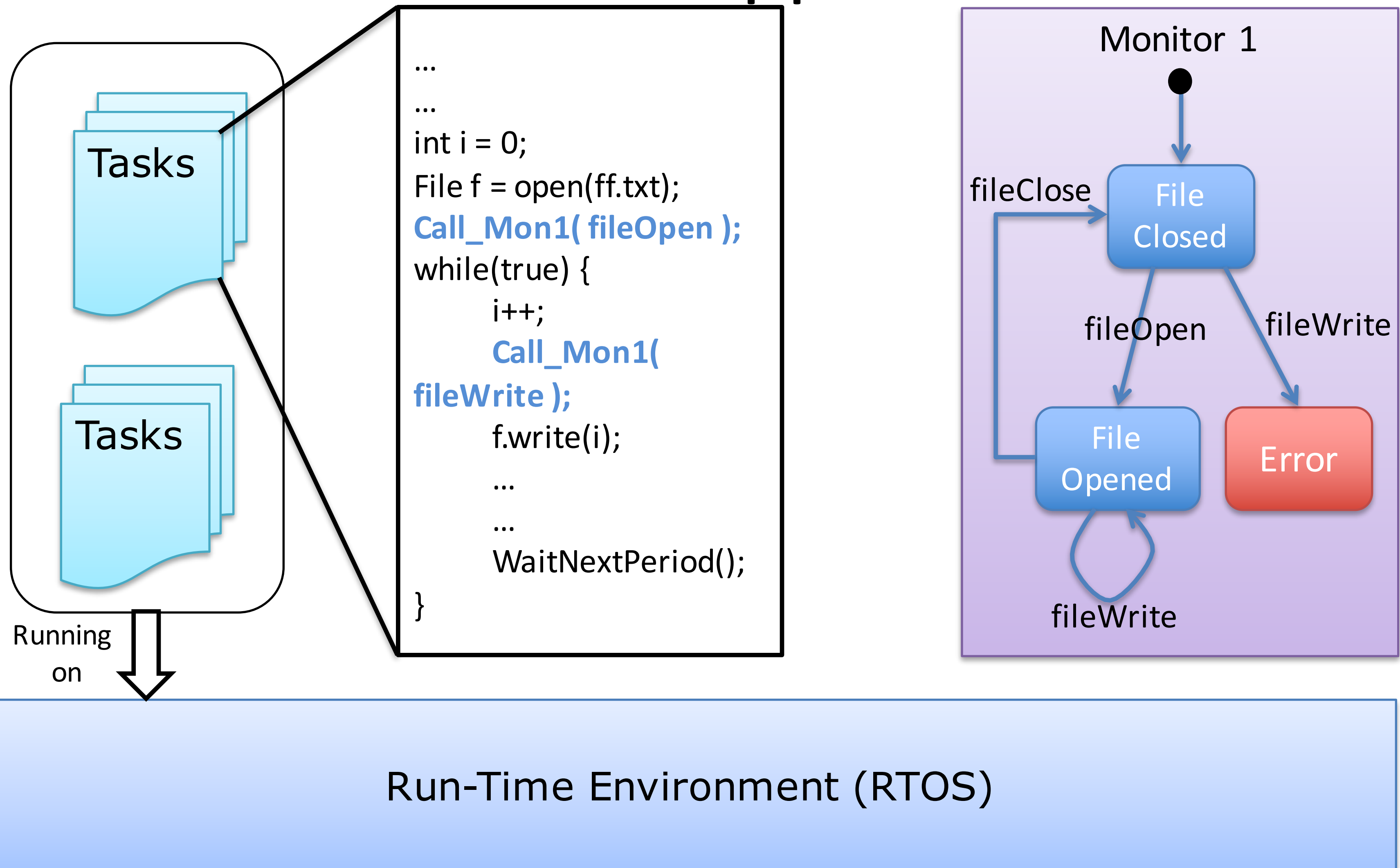


LIMITATIONS OF CURRENT ARCHITECTURES

Change Timing Properties of the Monitored Application



Change Timing Properties of the Monitored Application



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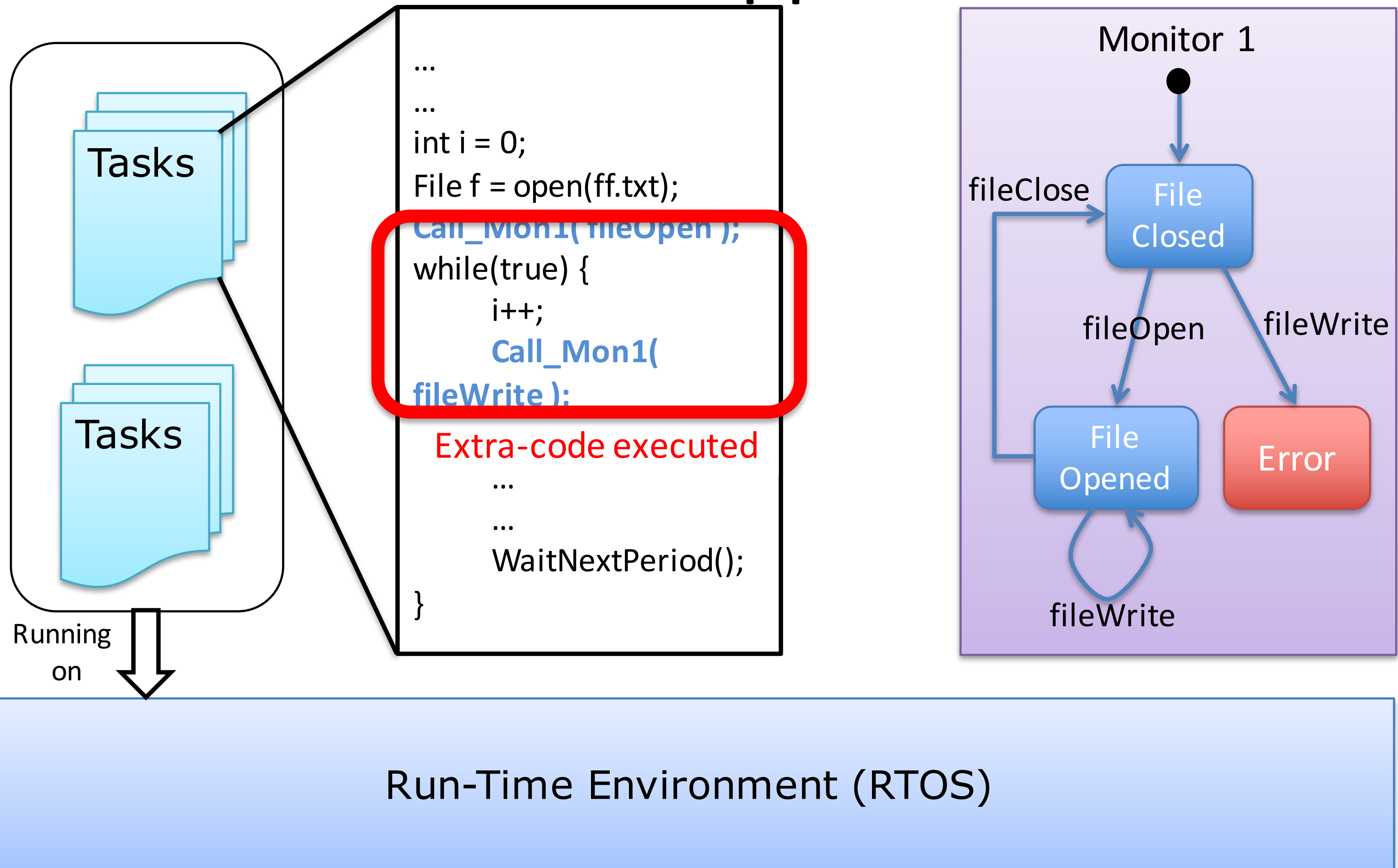

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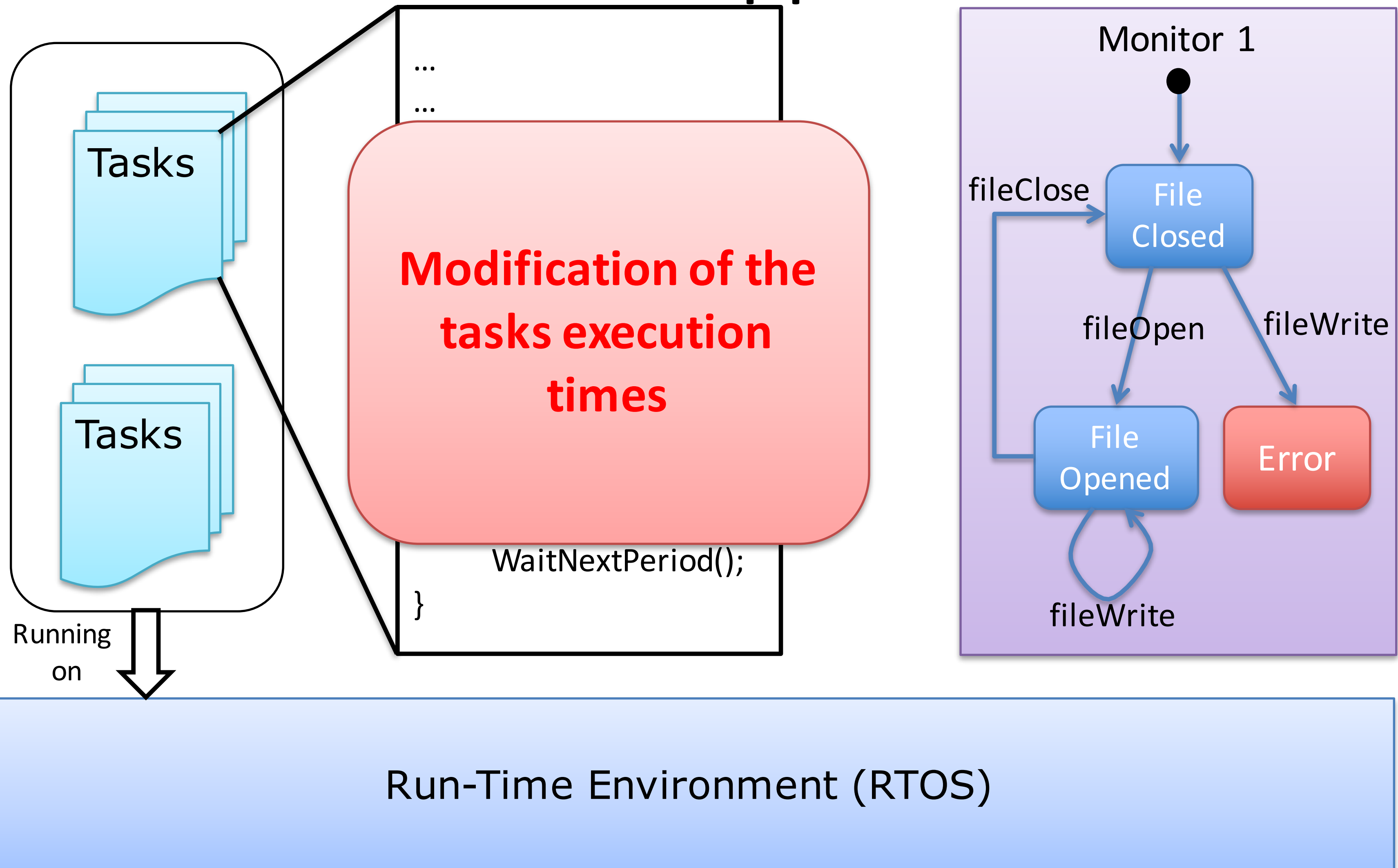
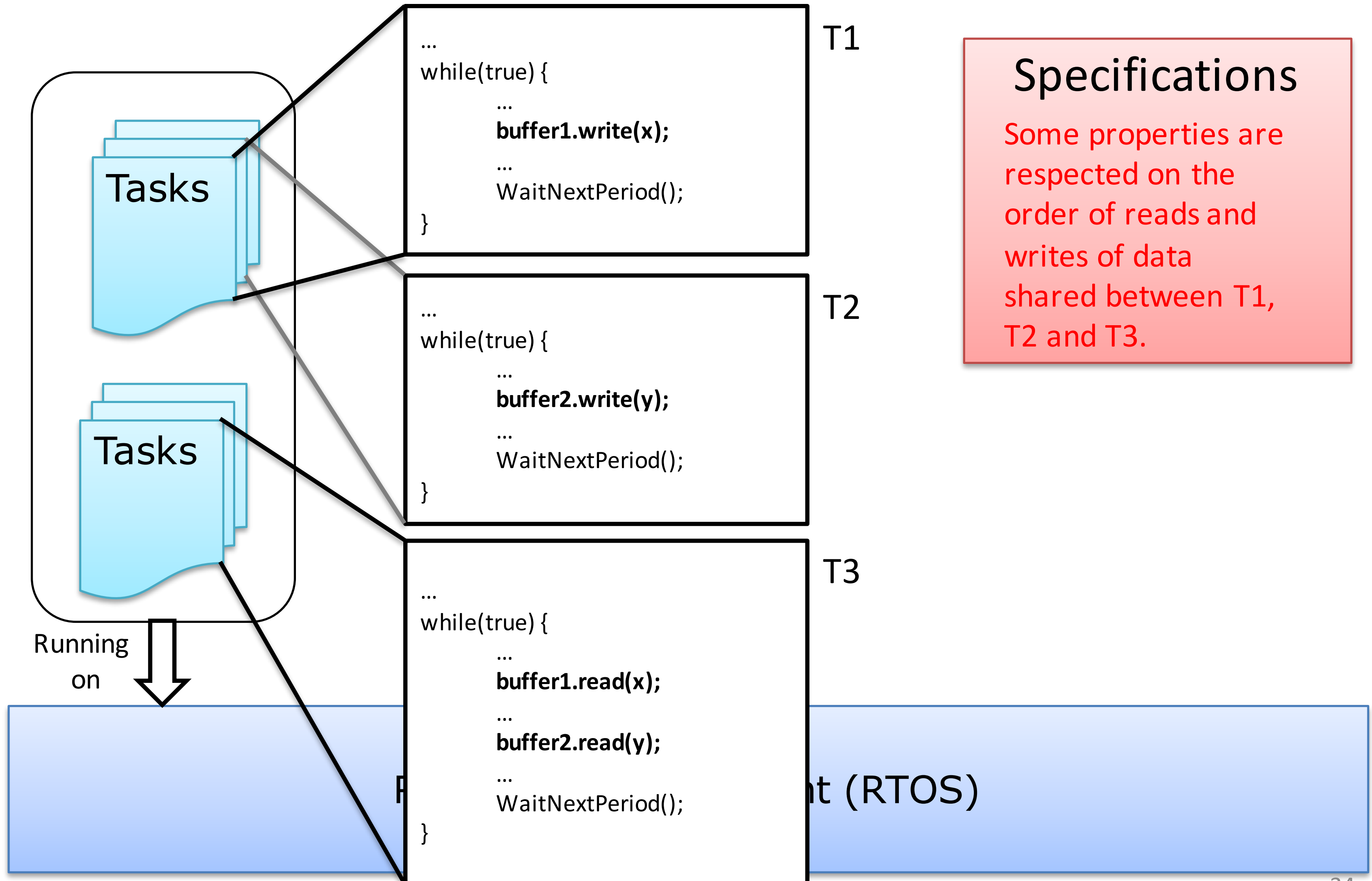


No Time Partitioning



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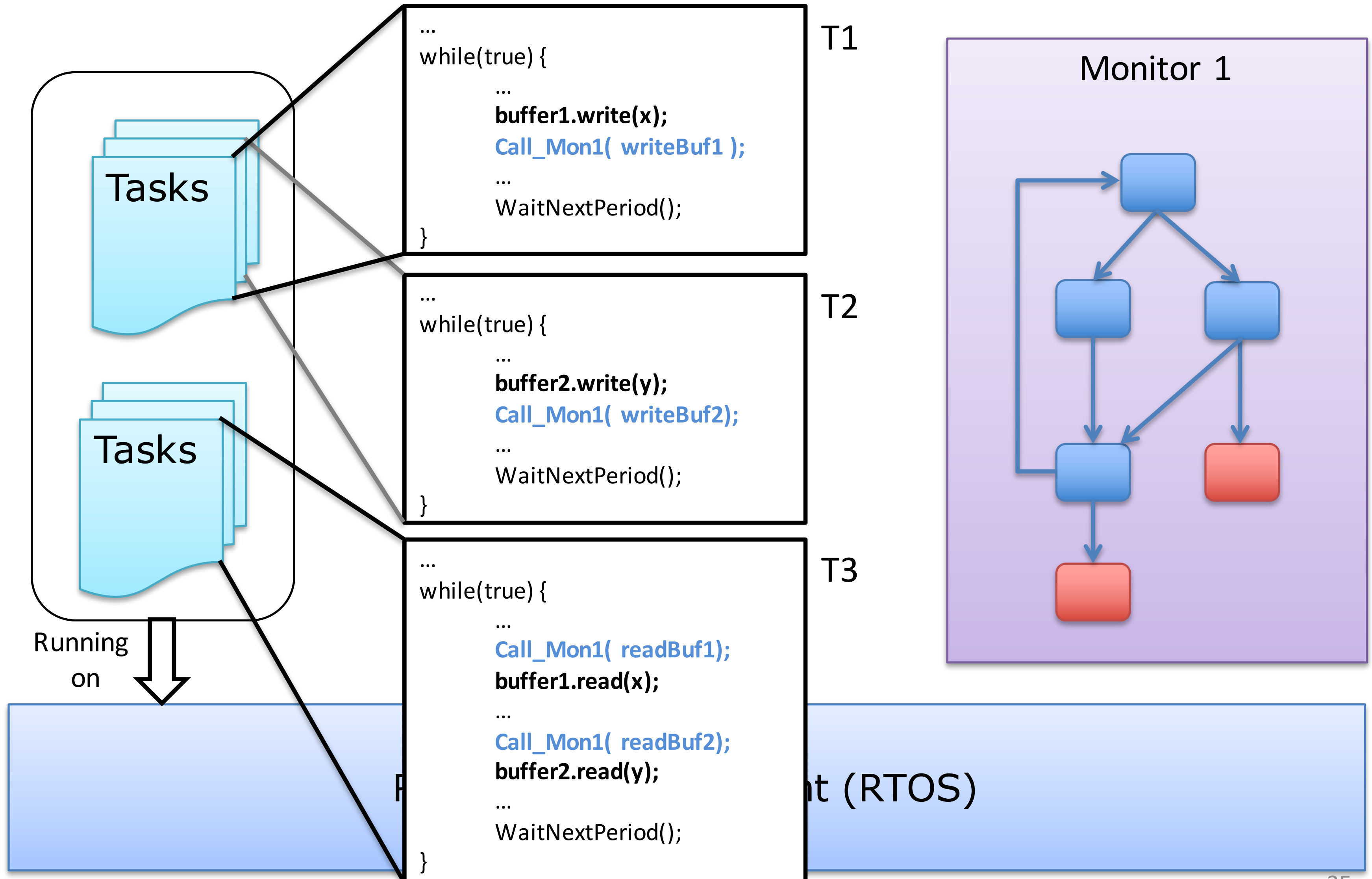

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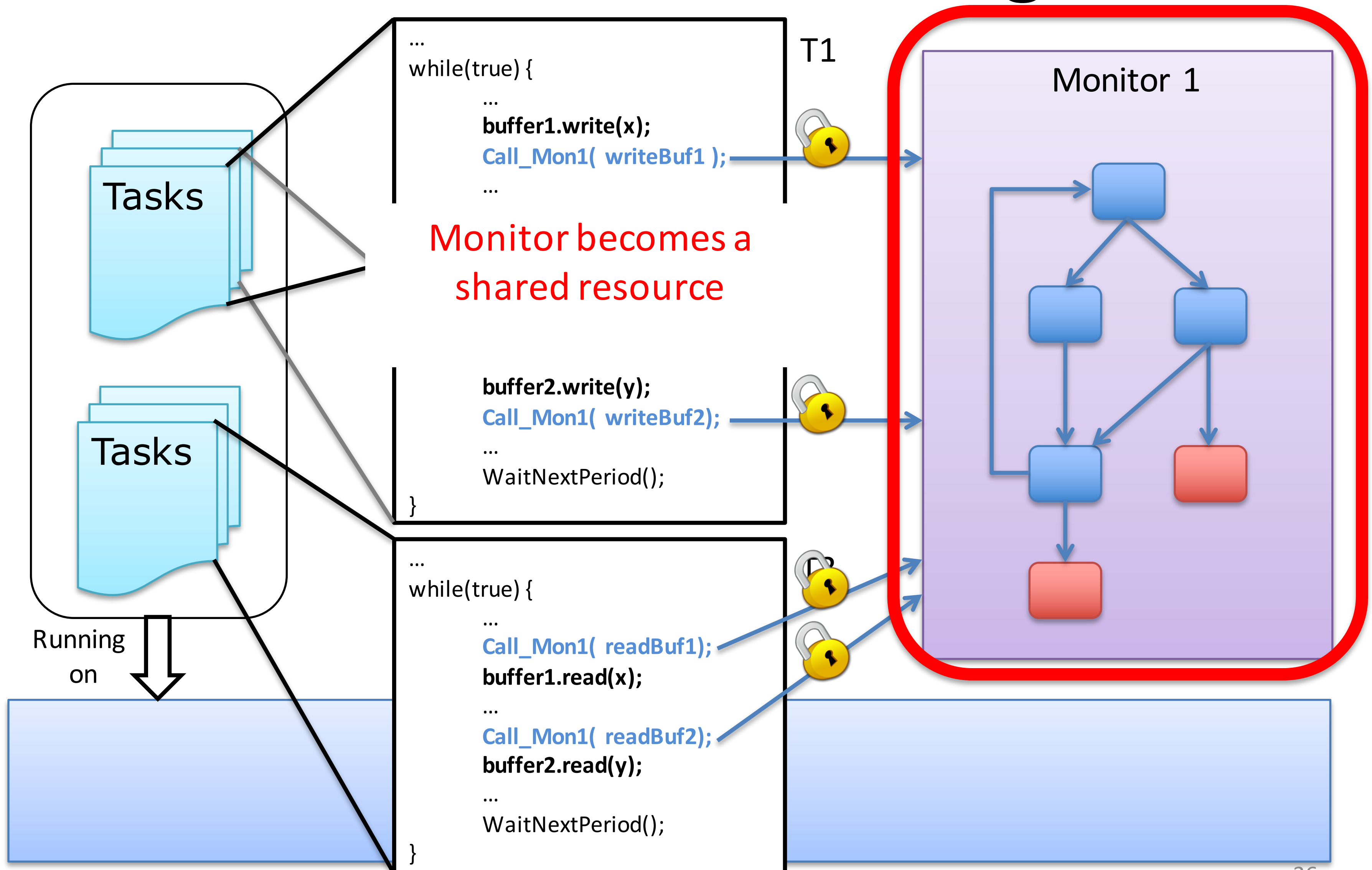

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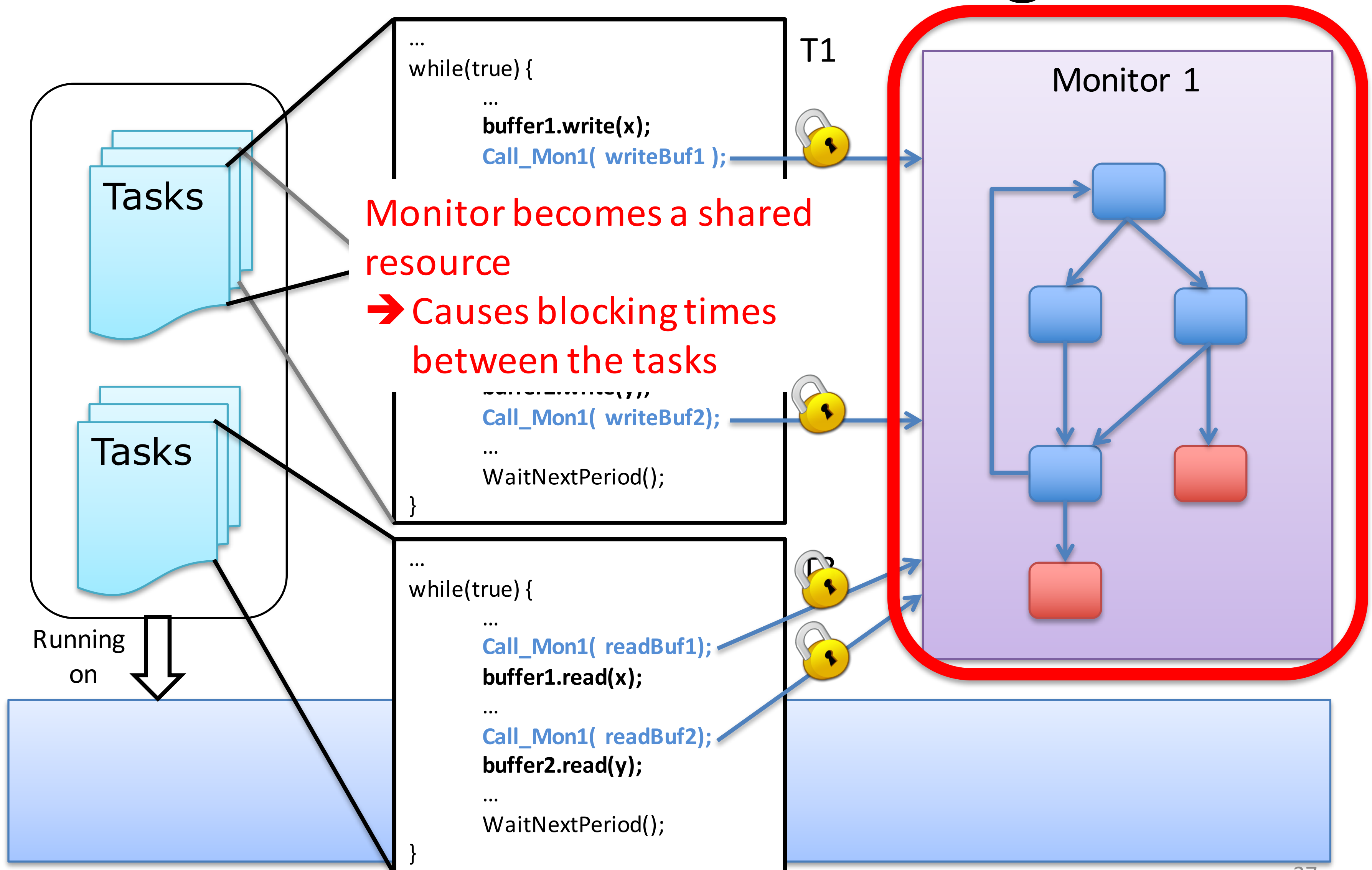

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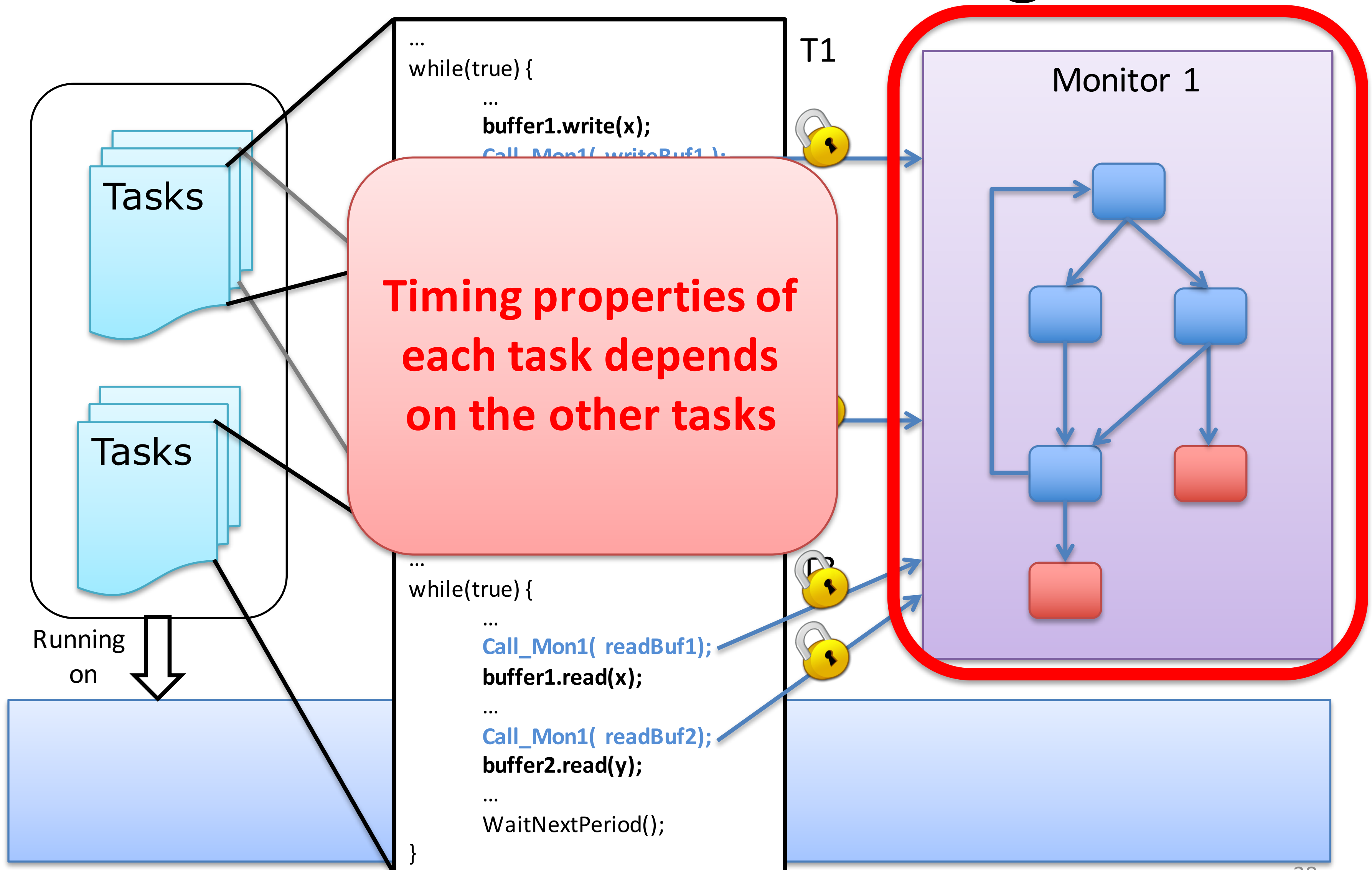
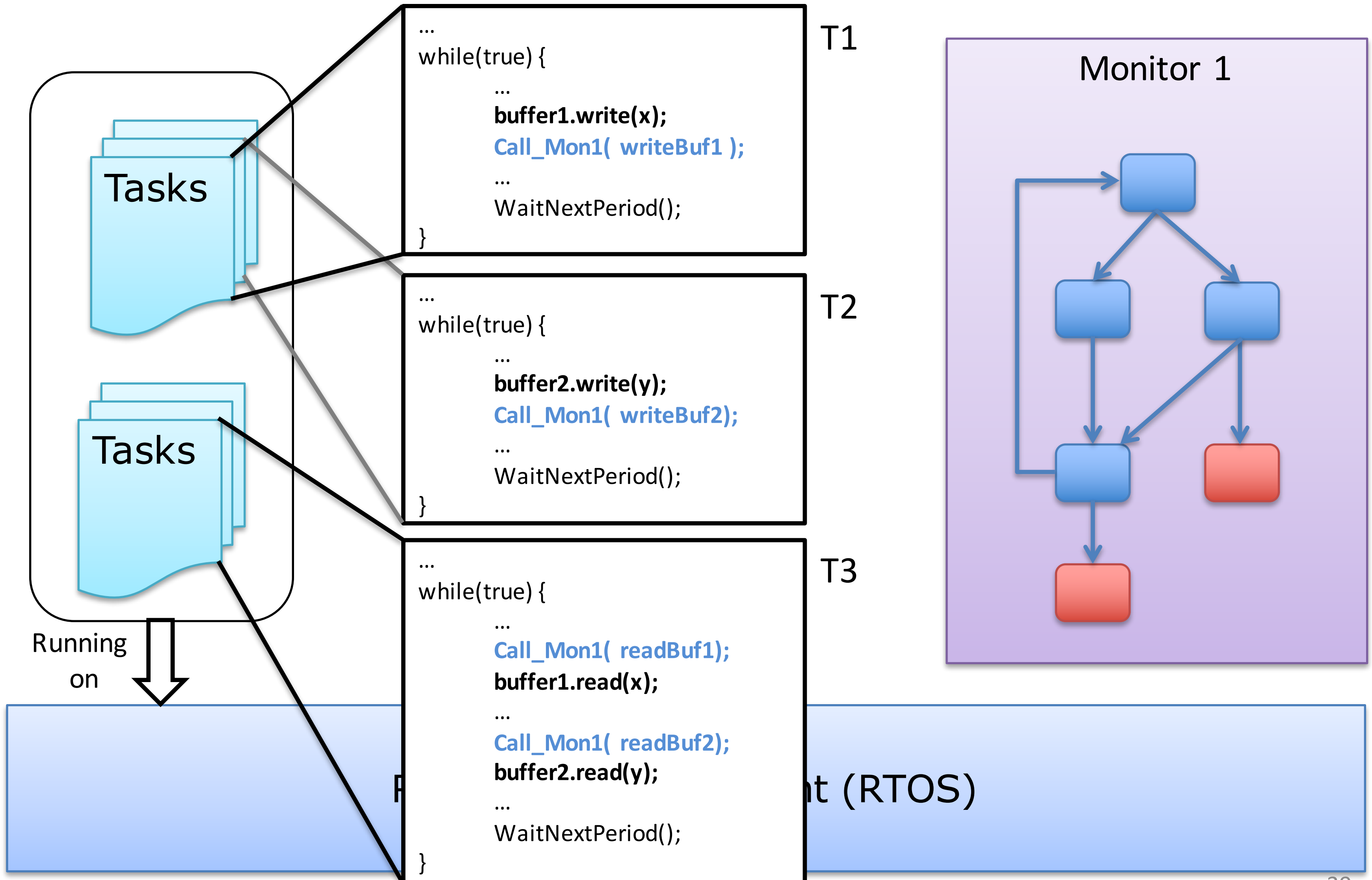


No Space Partitioning



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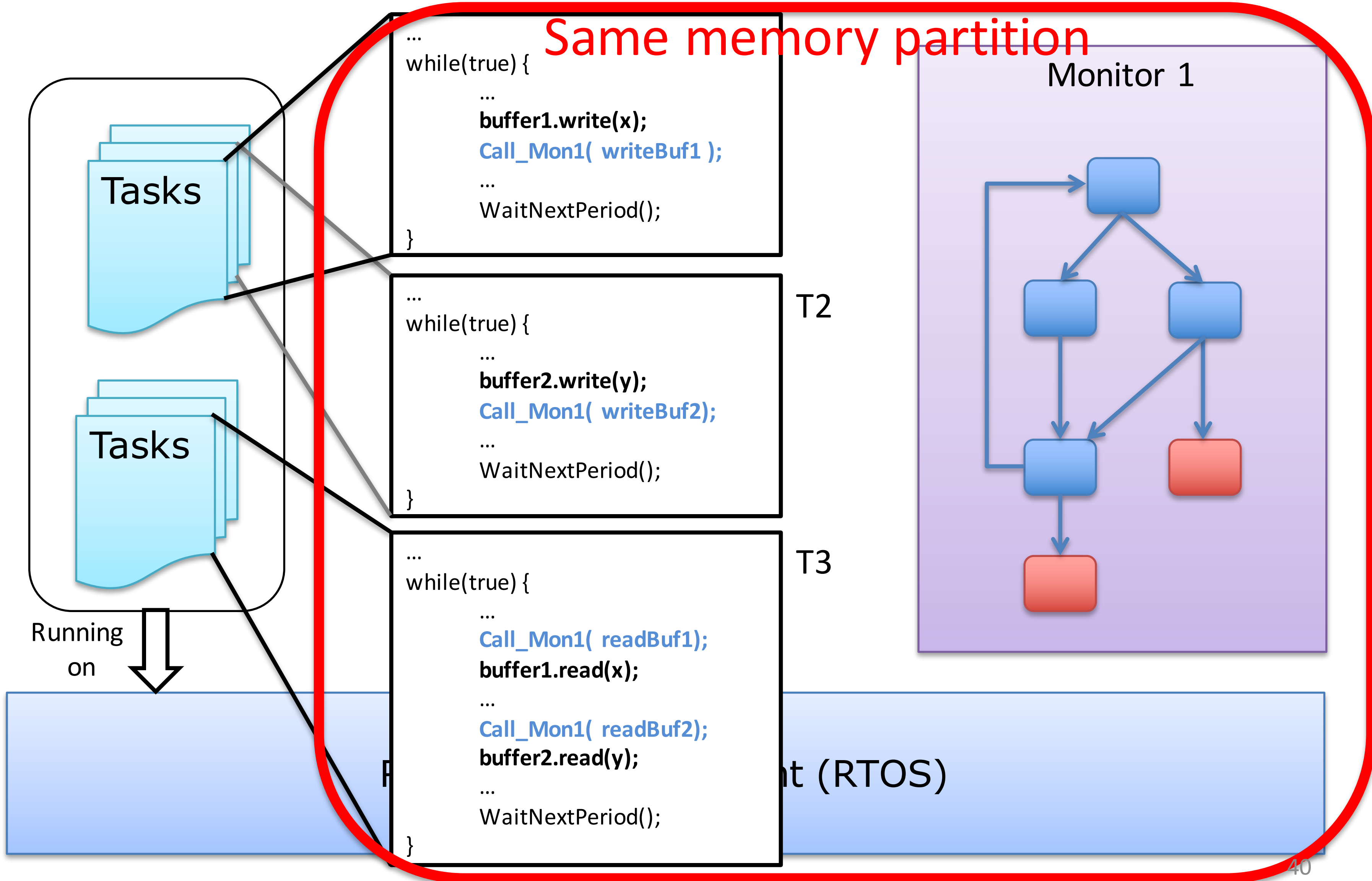

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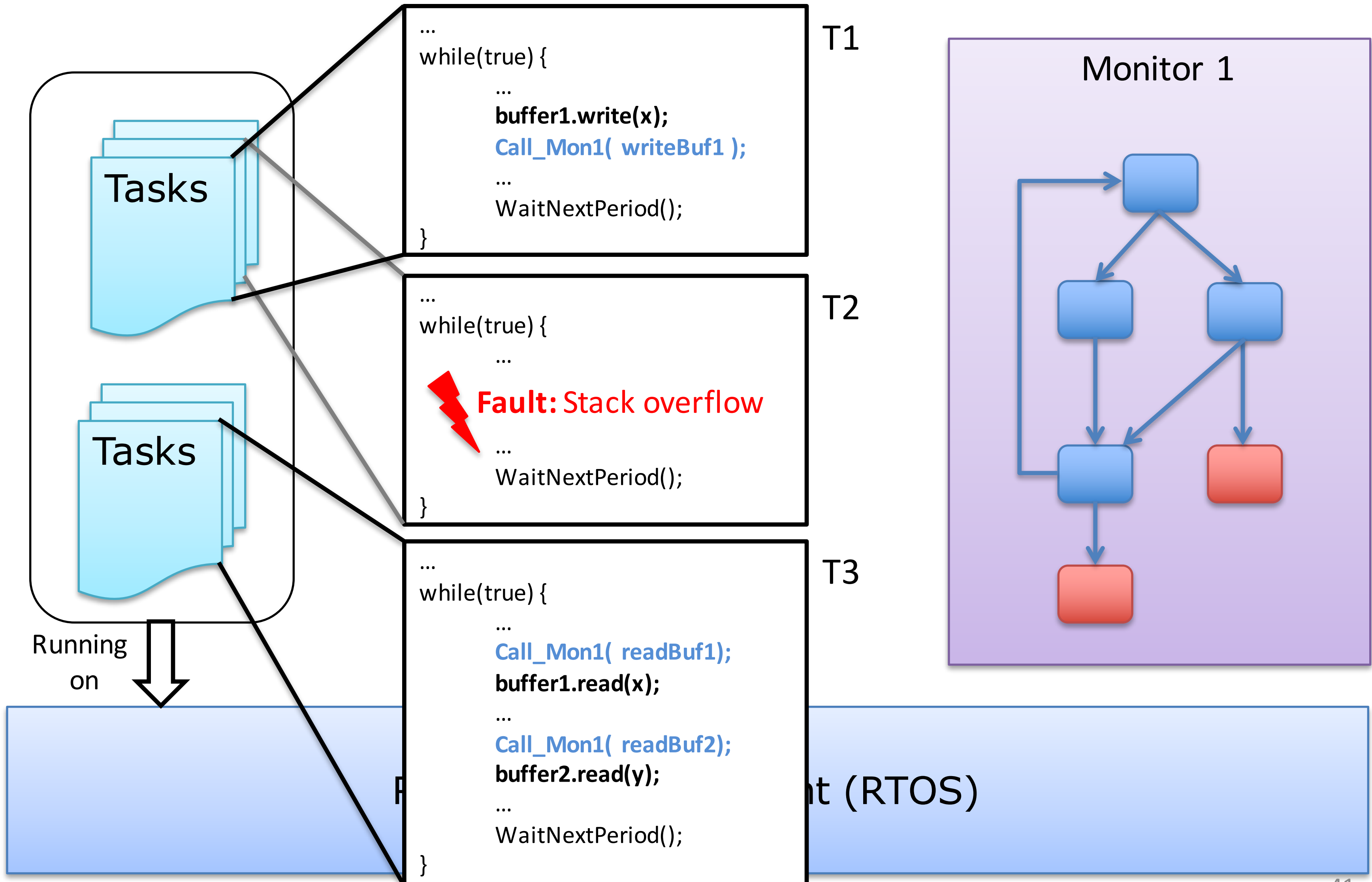

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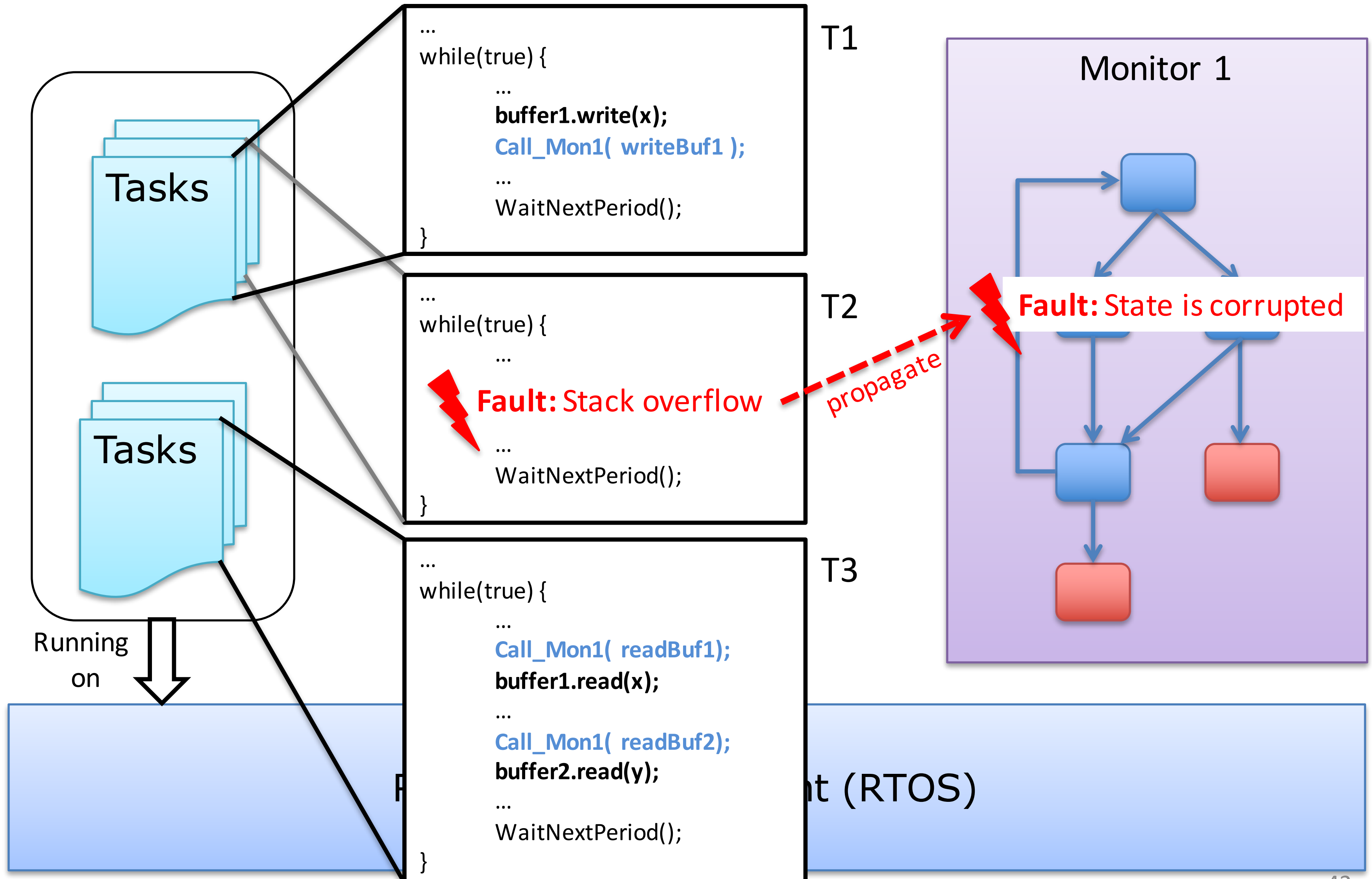

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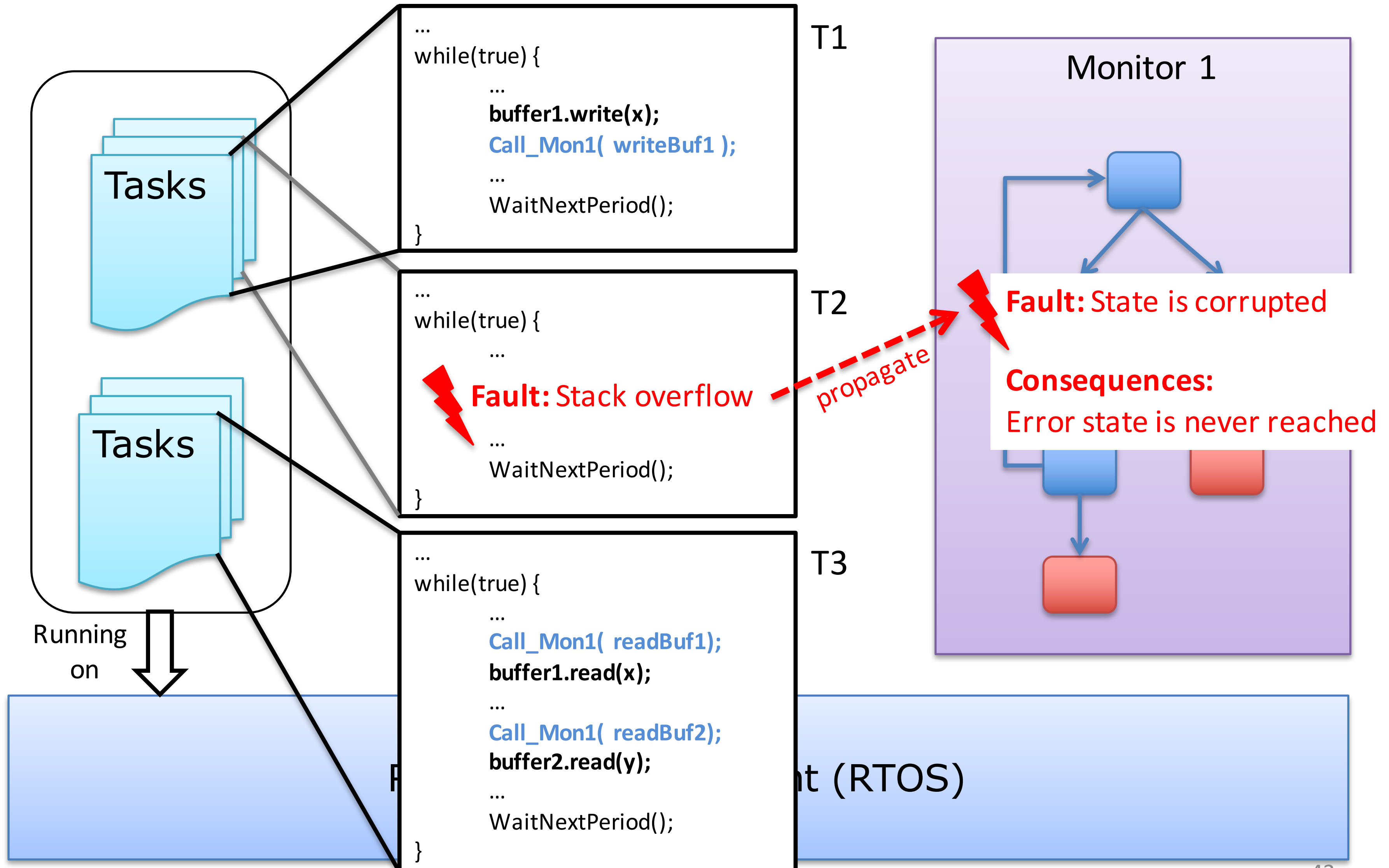

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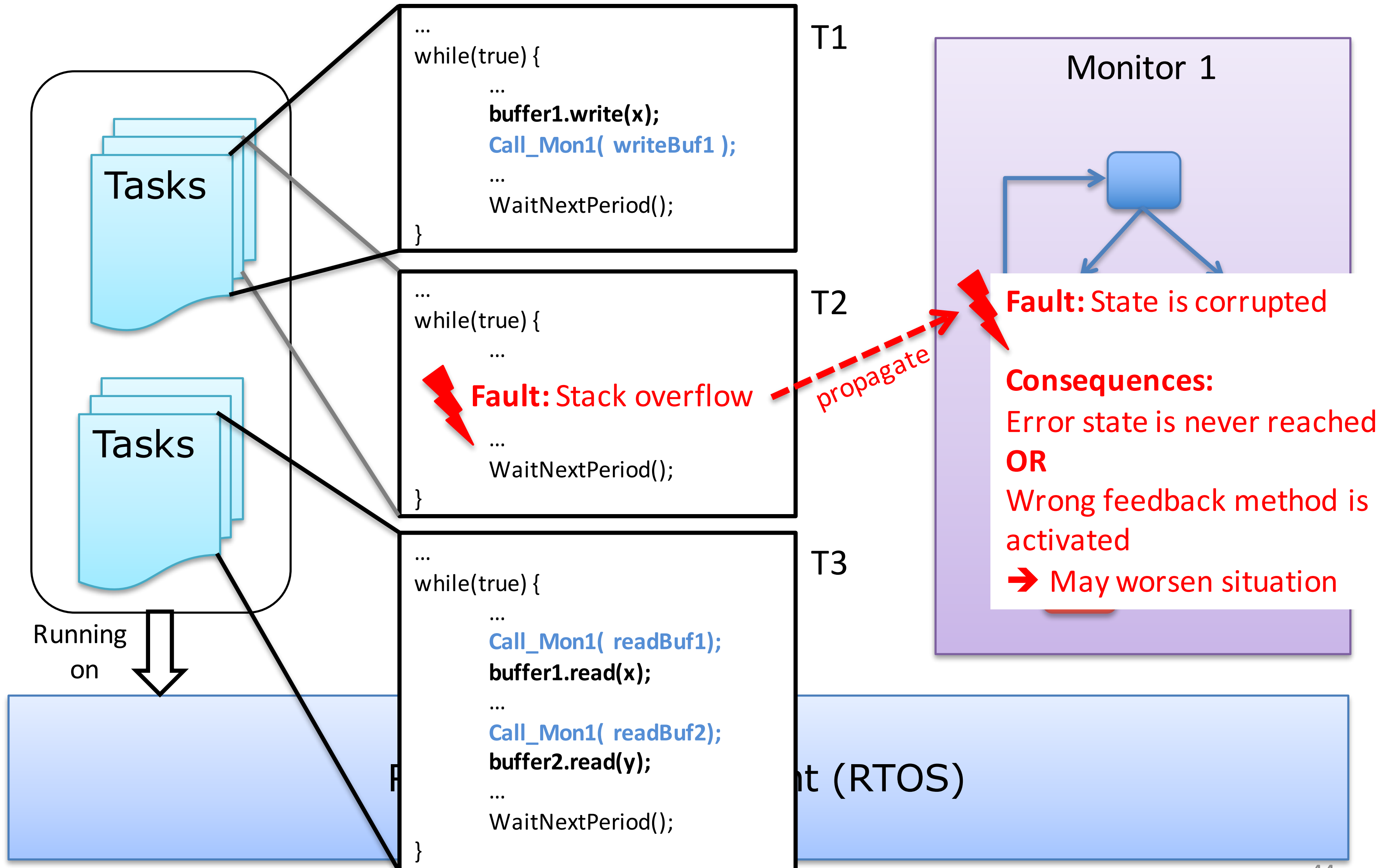

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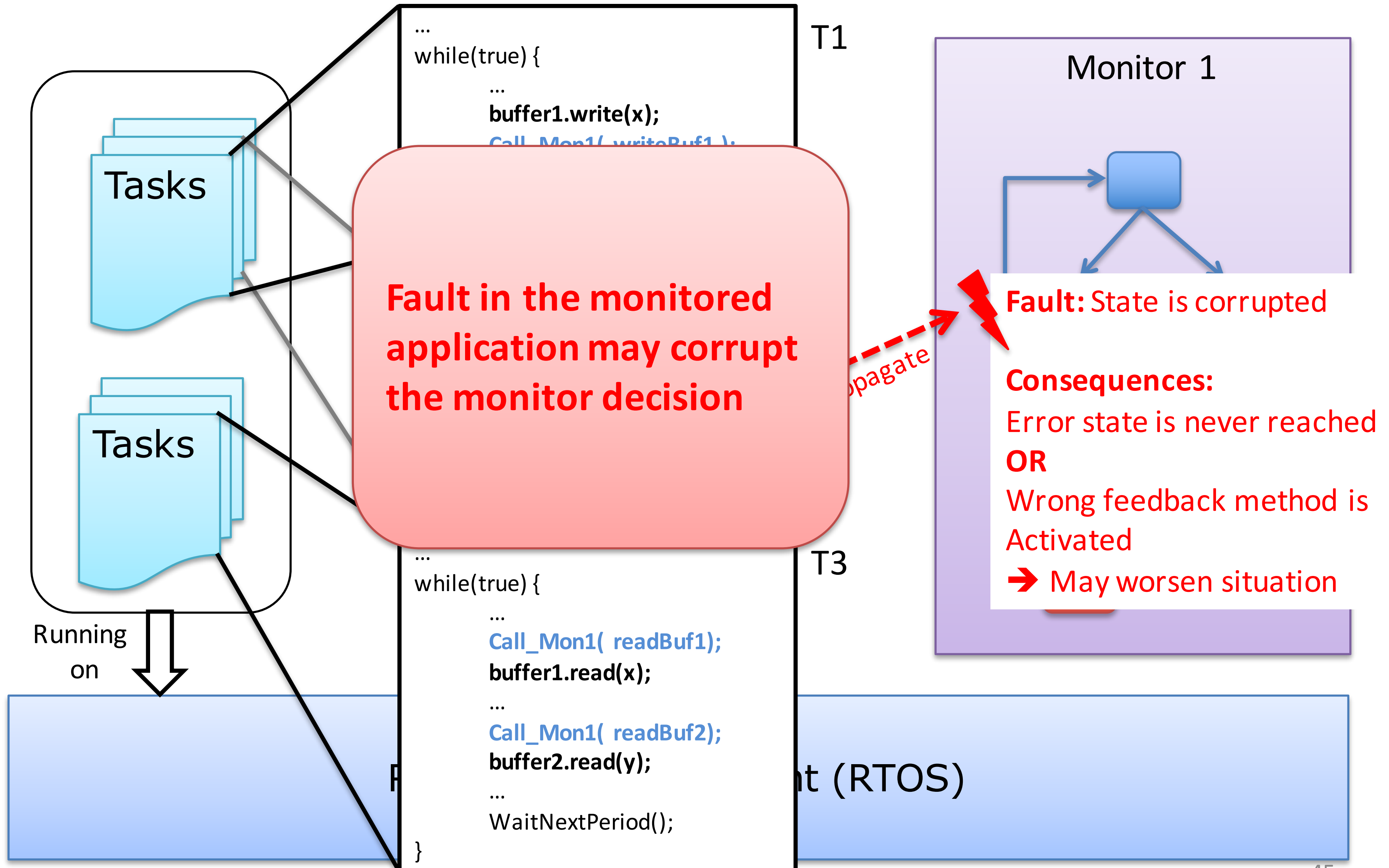
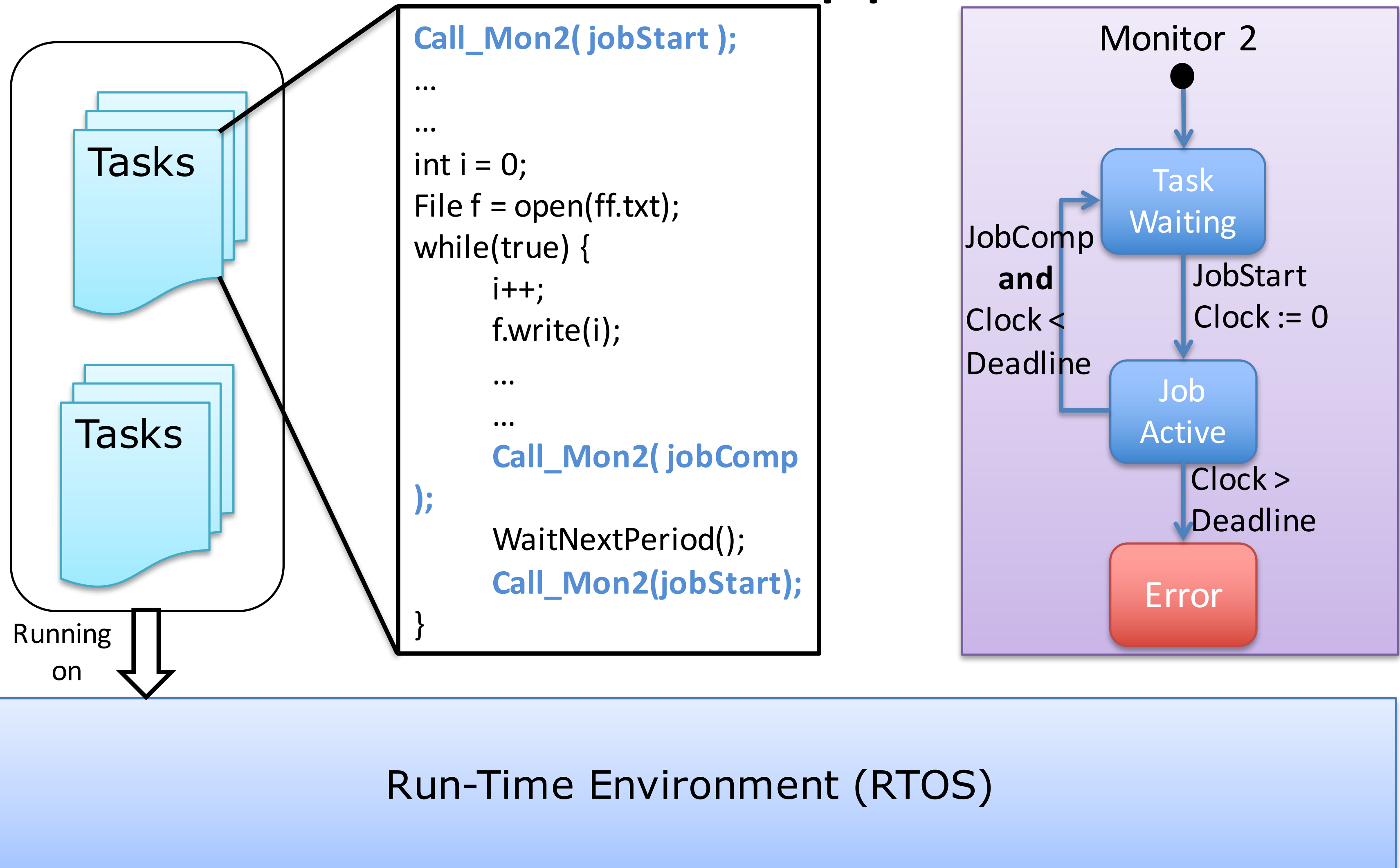


No Independence between Monitors and Monitored Application



No Independence between Monitors and Monitored Application

Tasks

Tasks

Running on

```
Call_Mon2( jobStart );
…
…
	…
	Call_Mon2( jobComp );
	WaitNextPeriod();
	Call_Mon2(jobStart);
}
```

State of the monitor updated only when called by the task

Monitor 2

Task Waiting

JobStart
Clock := 0

Job Active

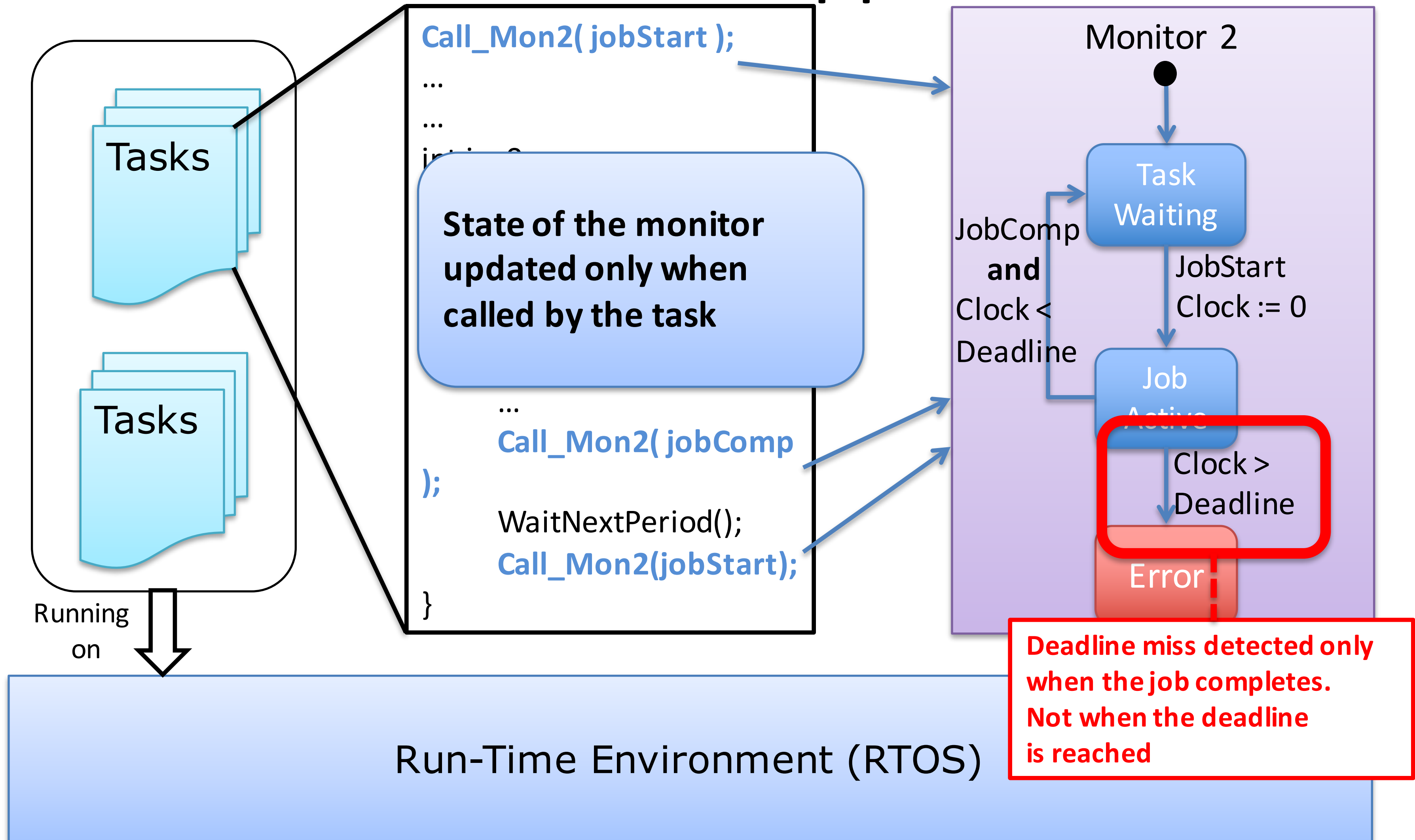
JobComp **and** Clock < Deadline

Clock > Deadline

Error

Run-Time Environment (RTOS)

No Independence between Monitors and Monitored Application



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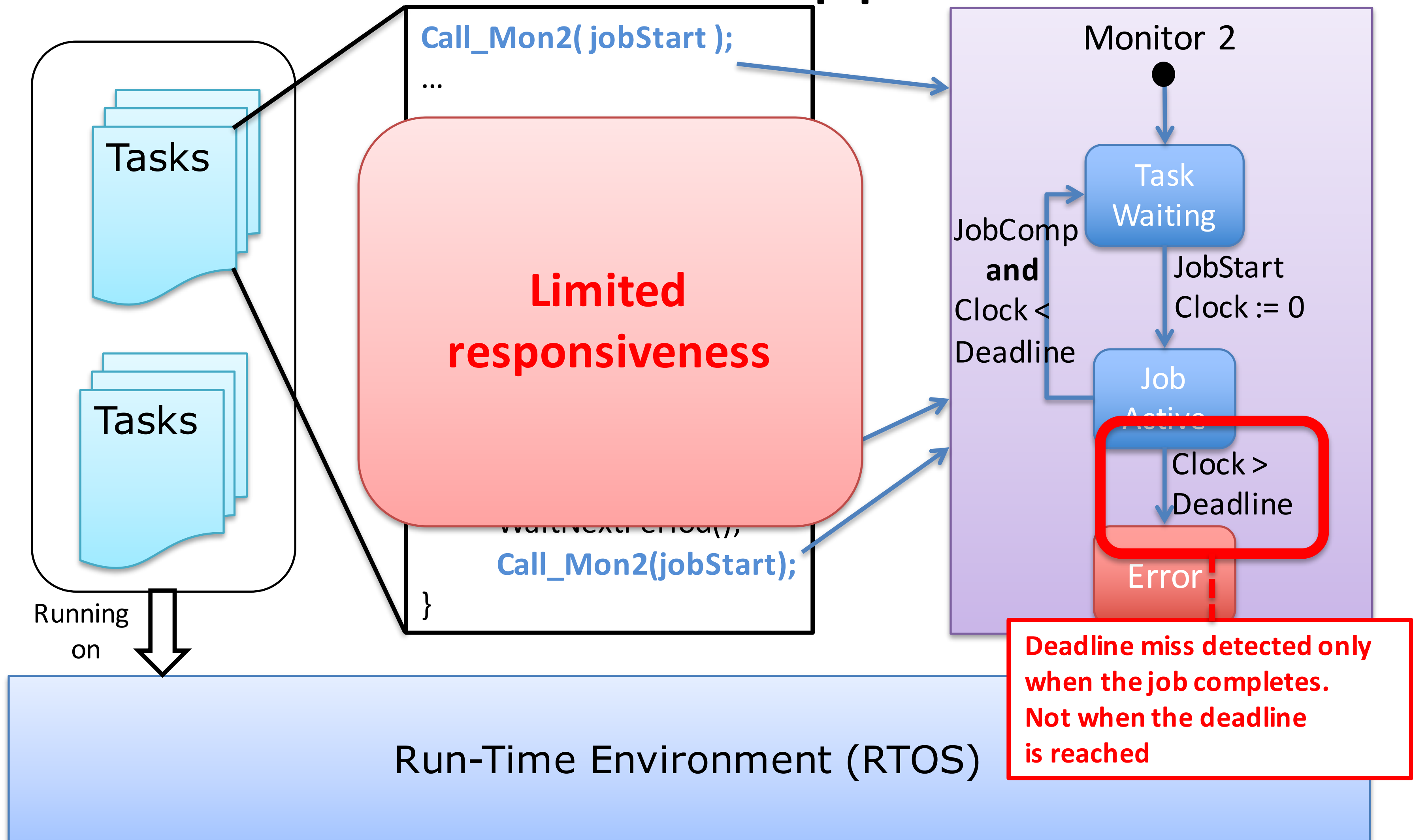

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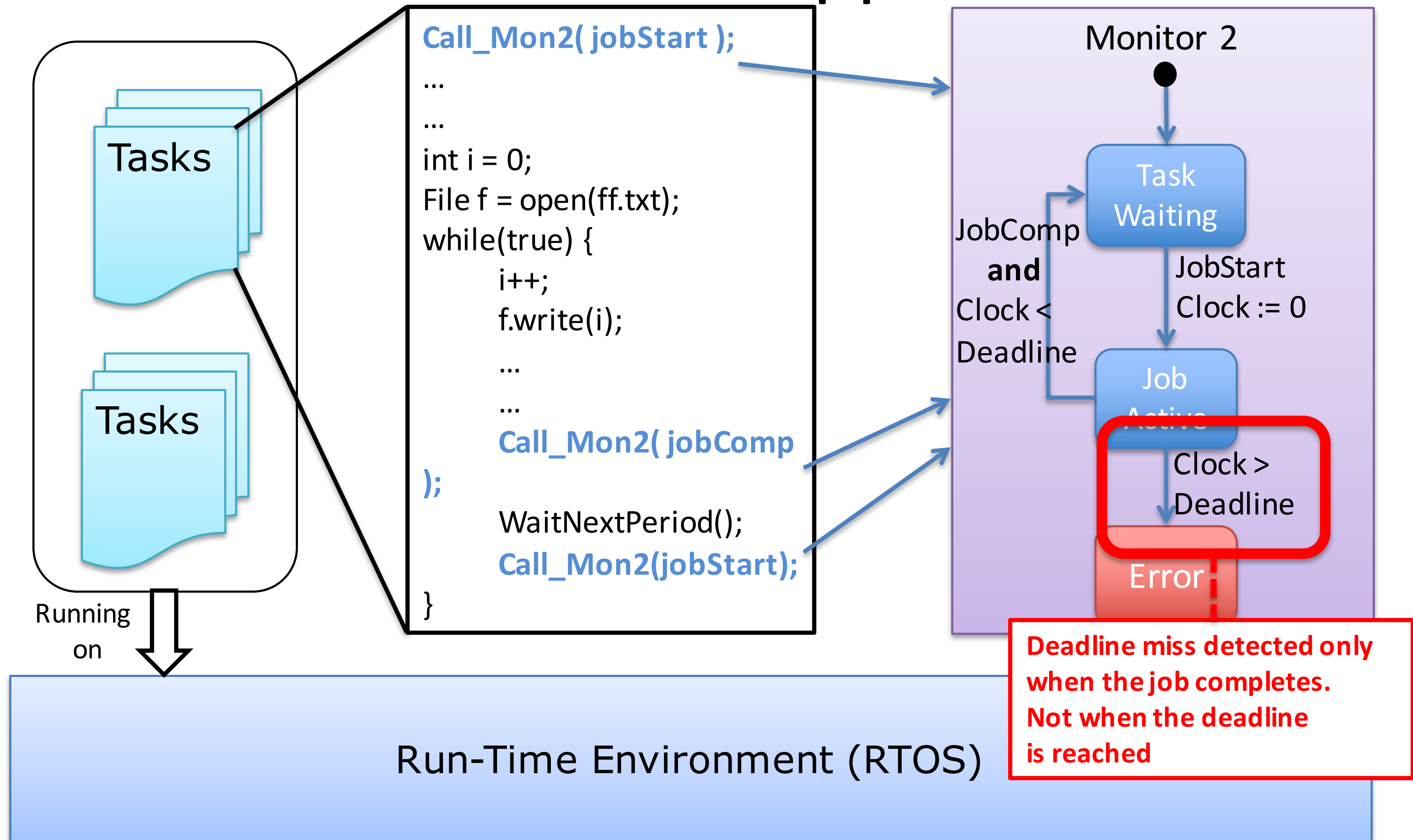

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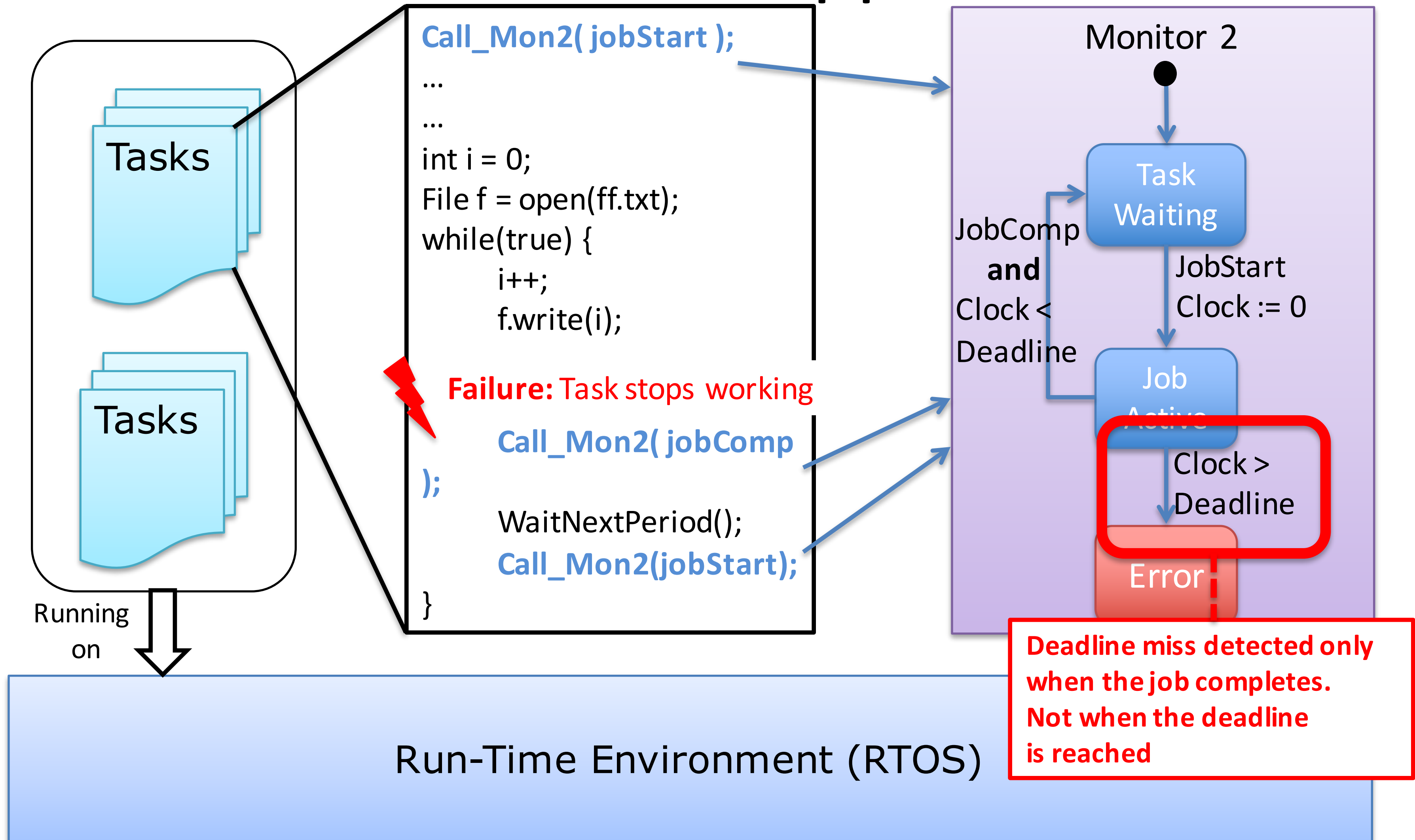

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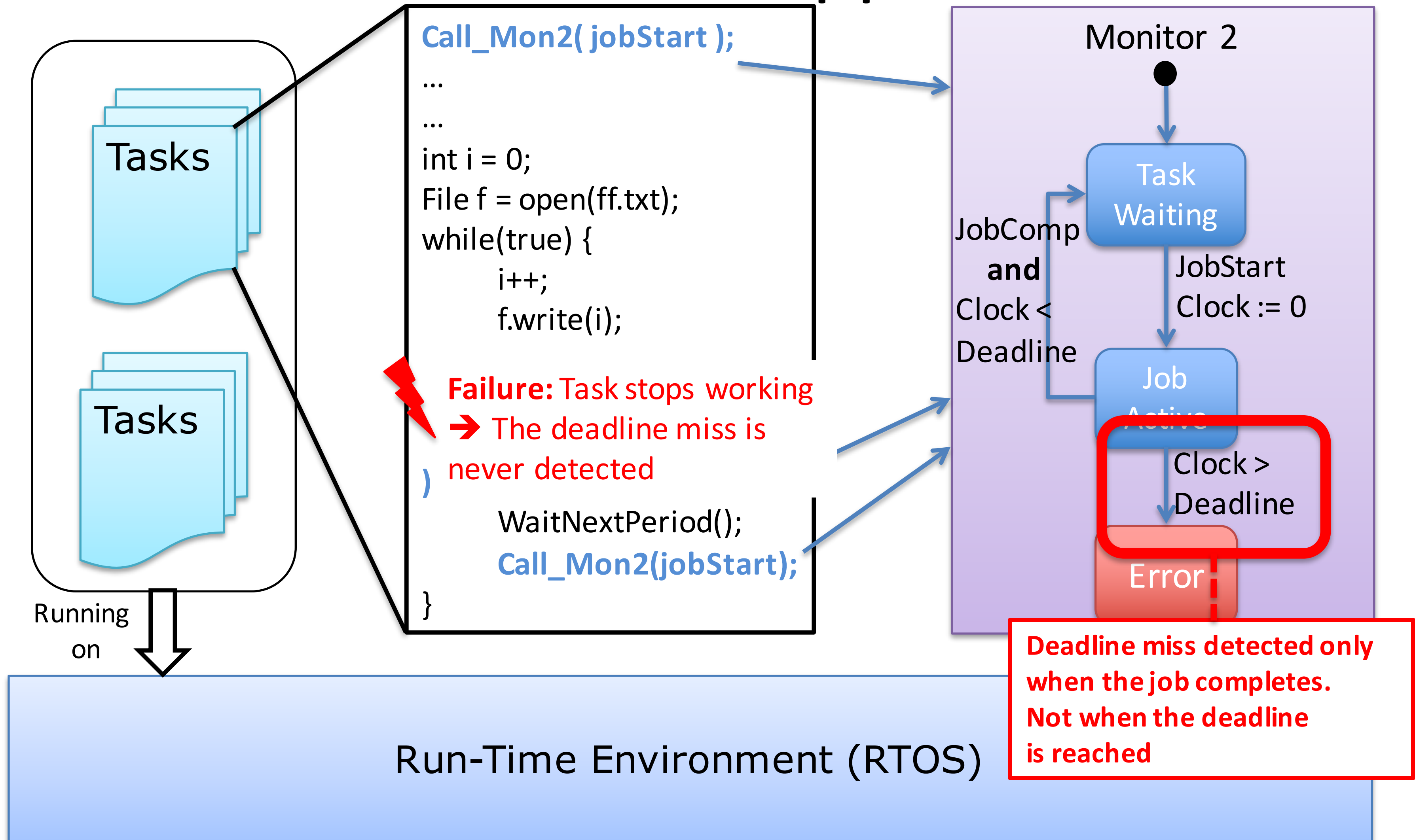

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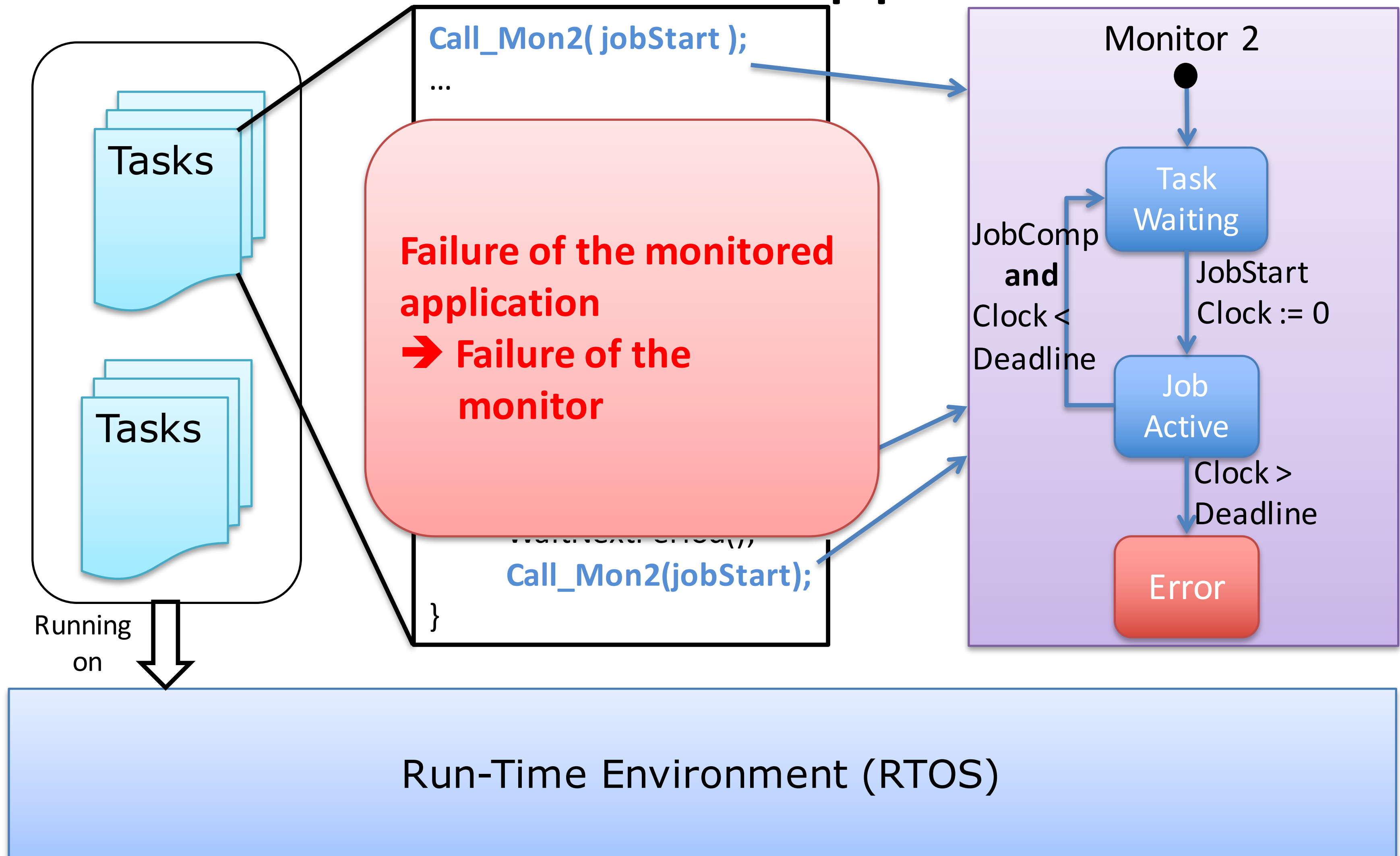
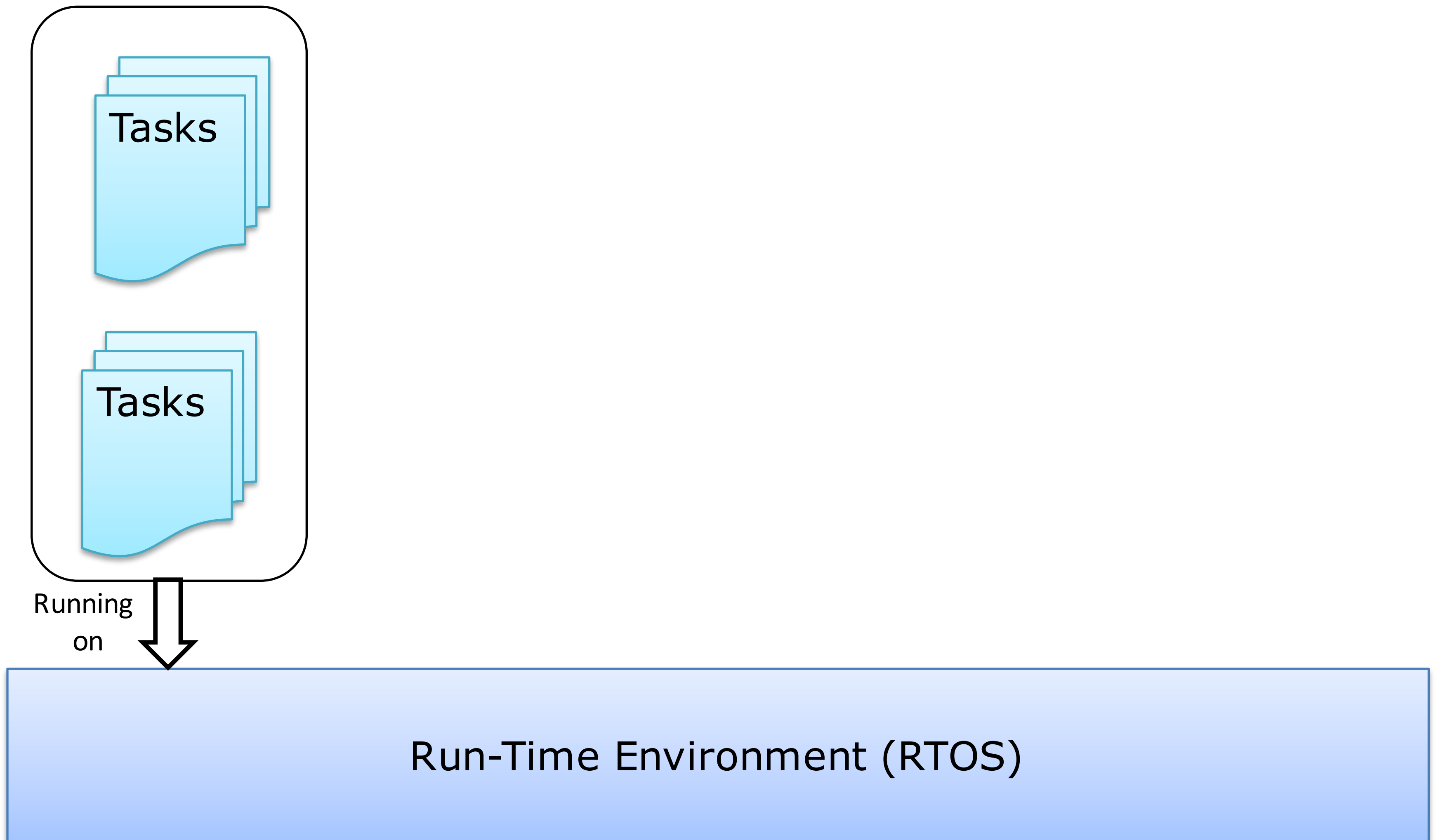


Limitations Summary

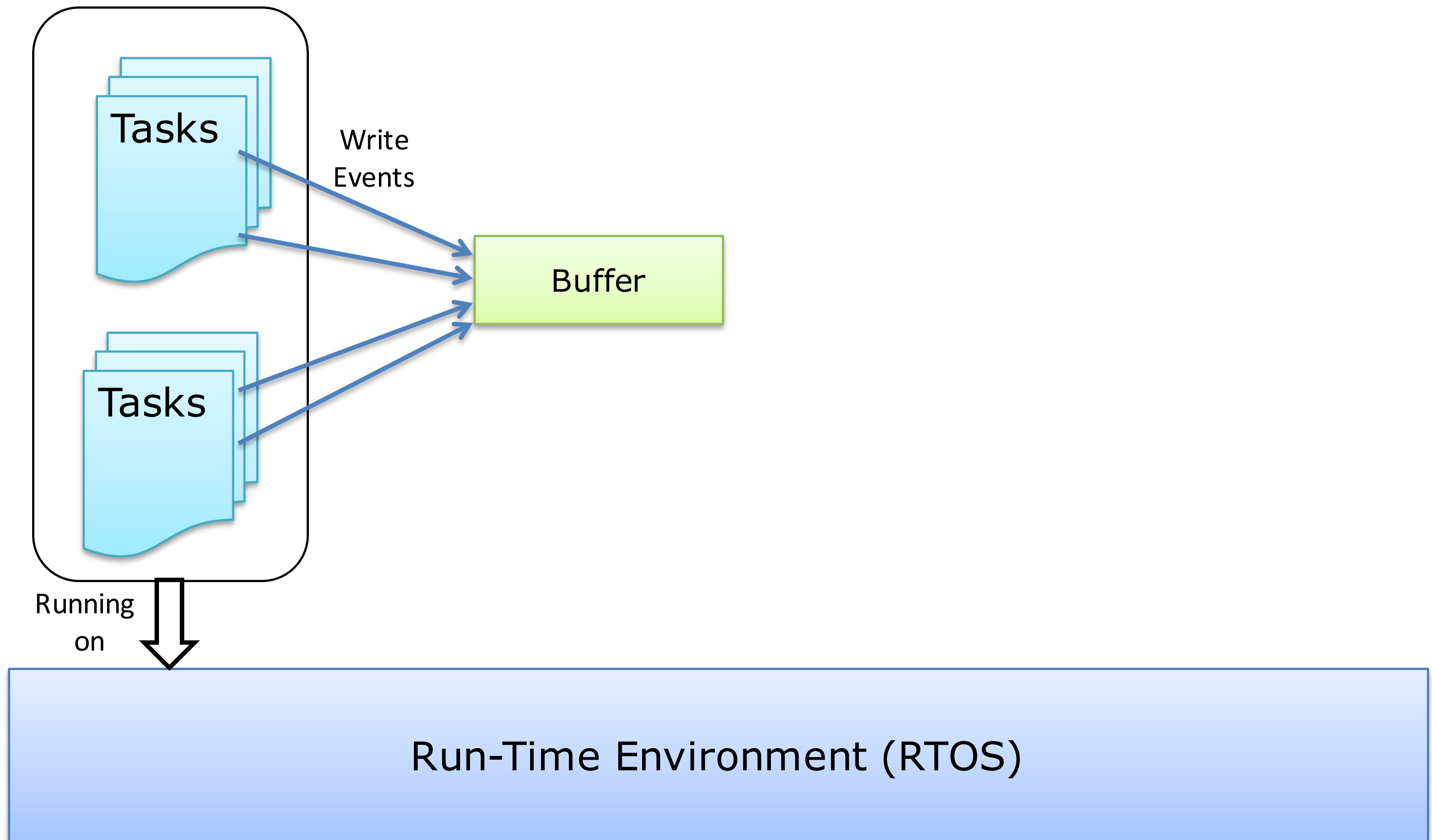
- Impact task execution times
- No time partitioning
  - Response time of one task is influenced by other tasks
- No space partitioning
  - Possible corruption of the monitor by a task and/or other monitors
- No independence between monitors and monitored application
  - Failure of the monitored task ➔ failure of the monitor
- Limited responsiveness

ALTERNATIVES IN THE STATE-OF-THE-ART

Framework Architecture



One Shared Buffer



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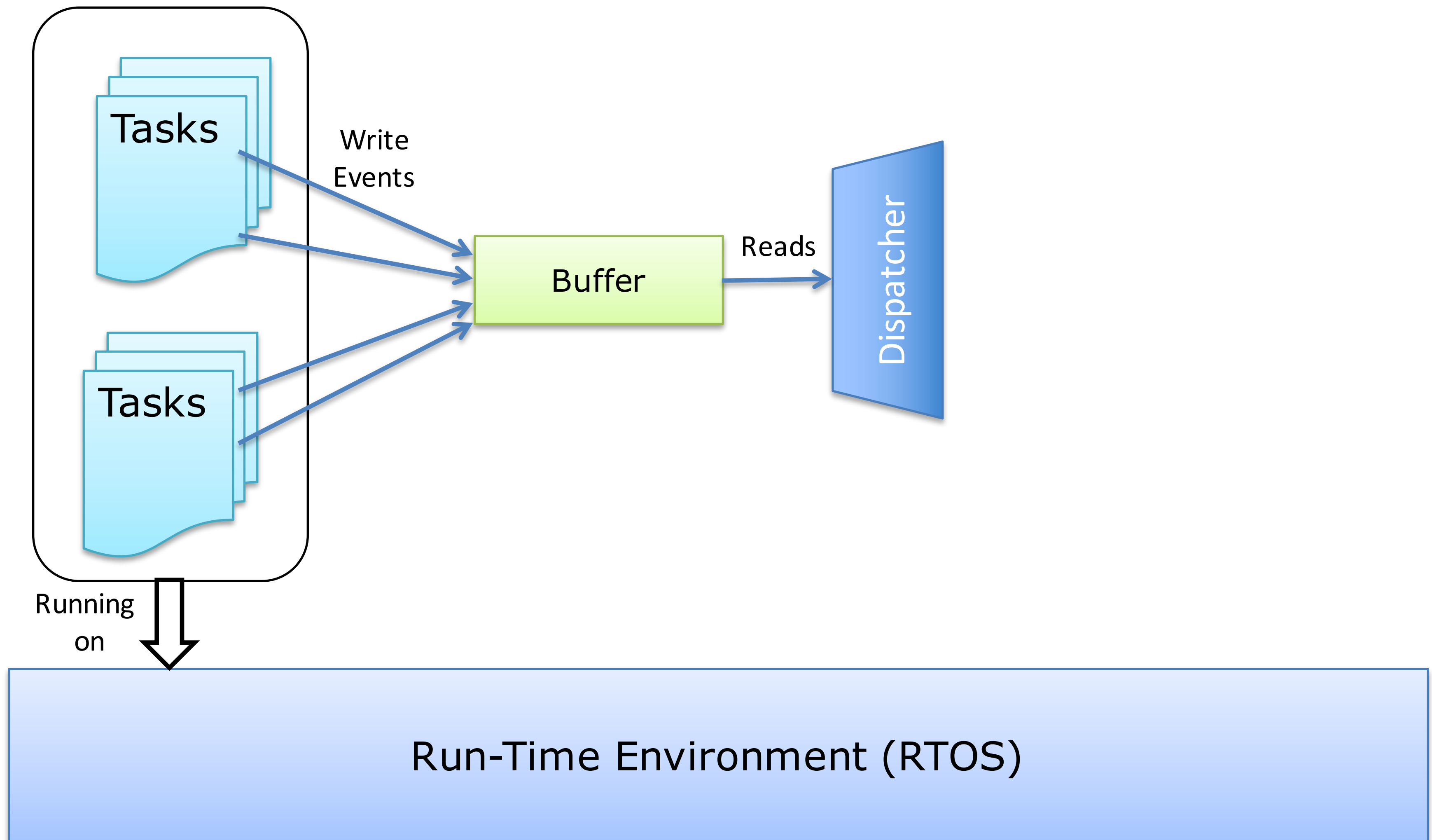

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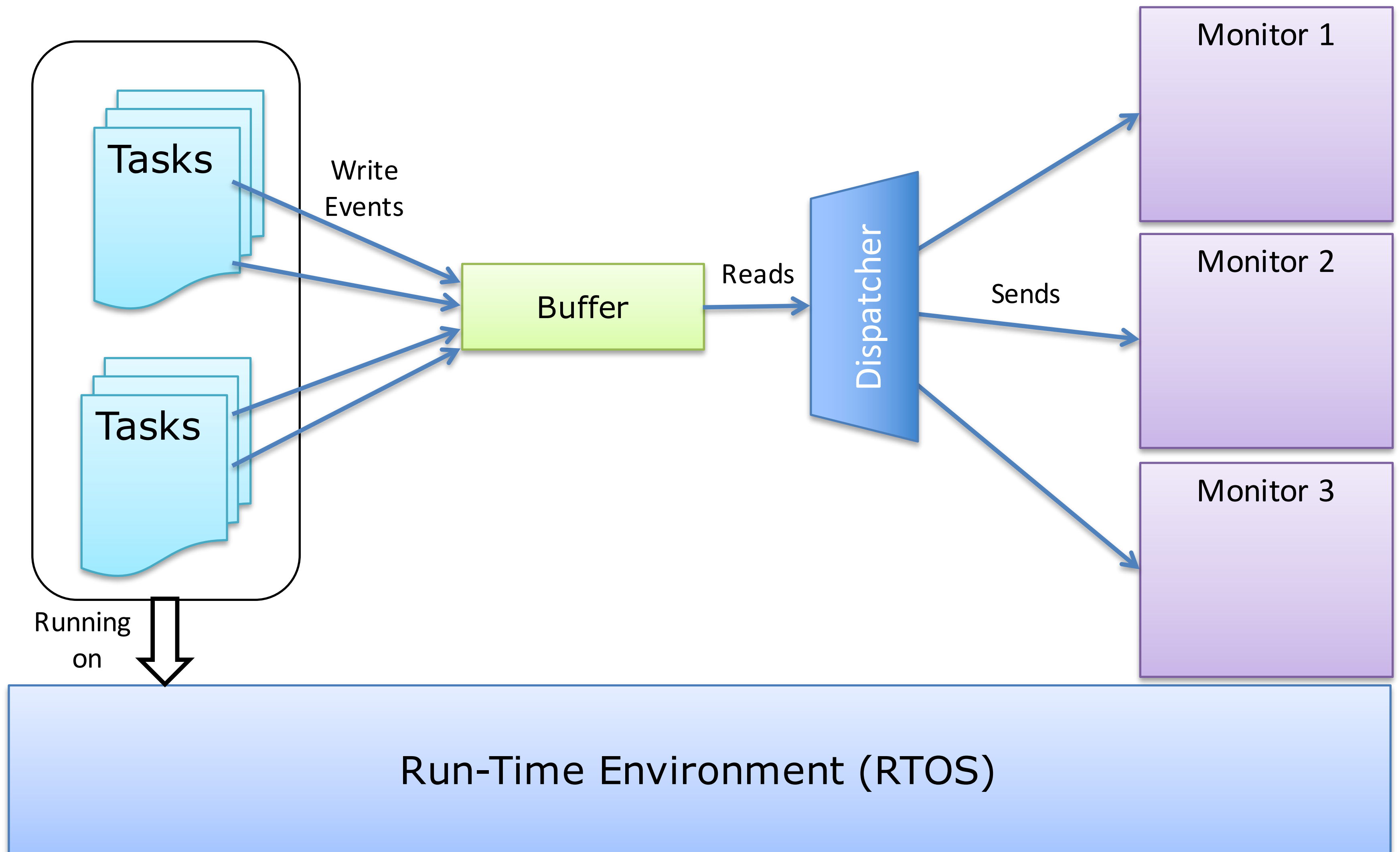

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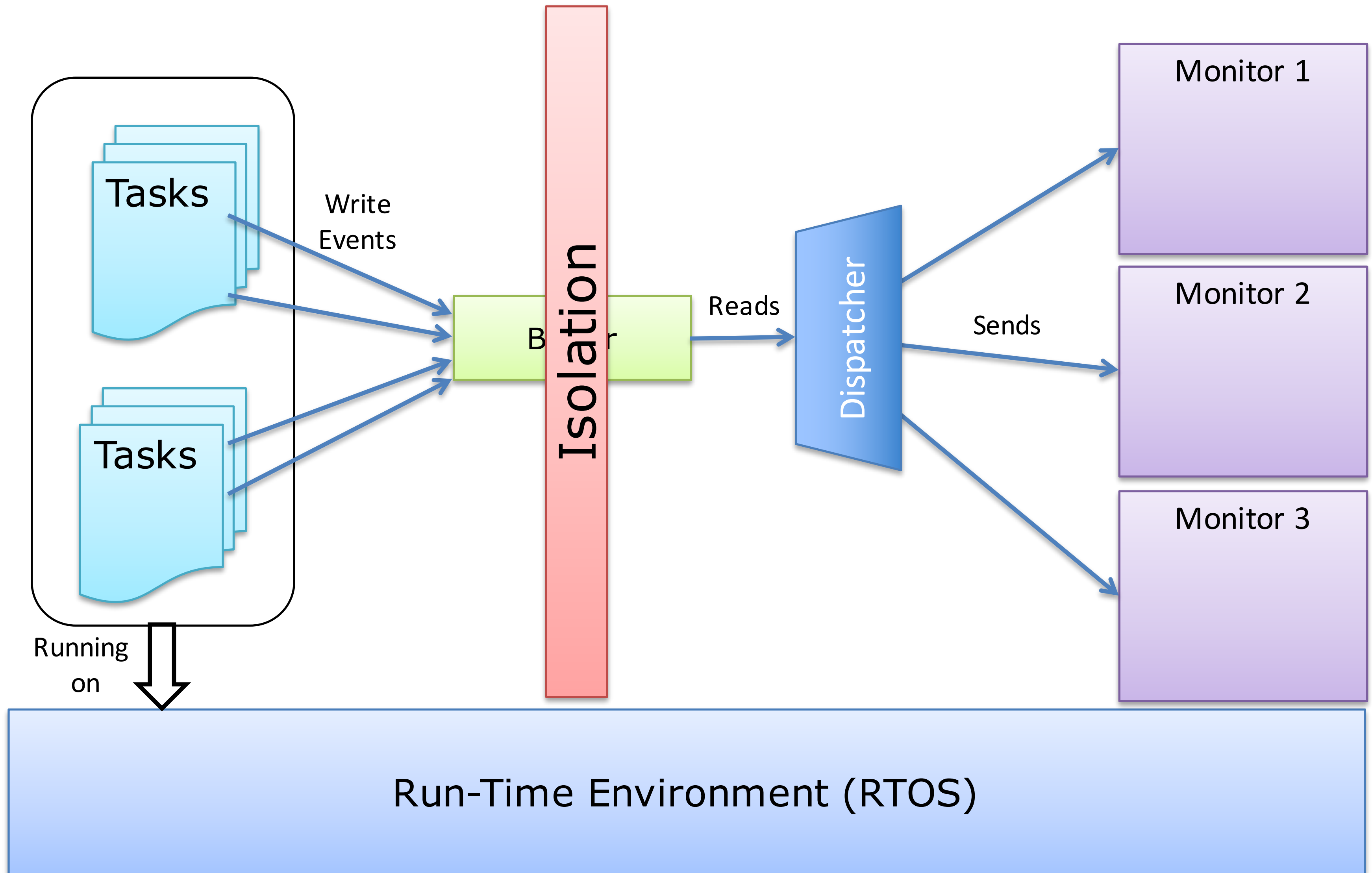

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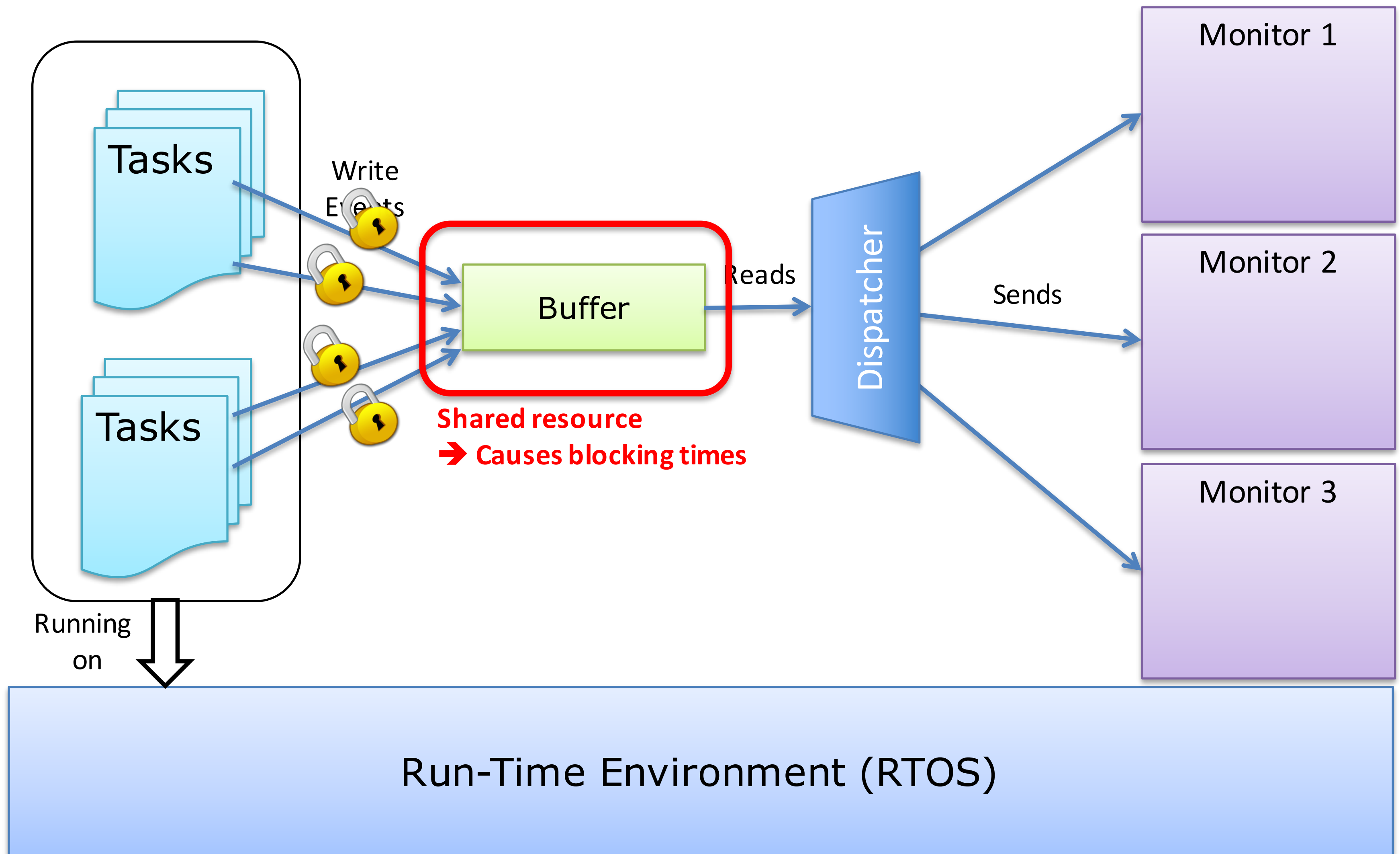

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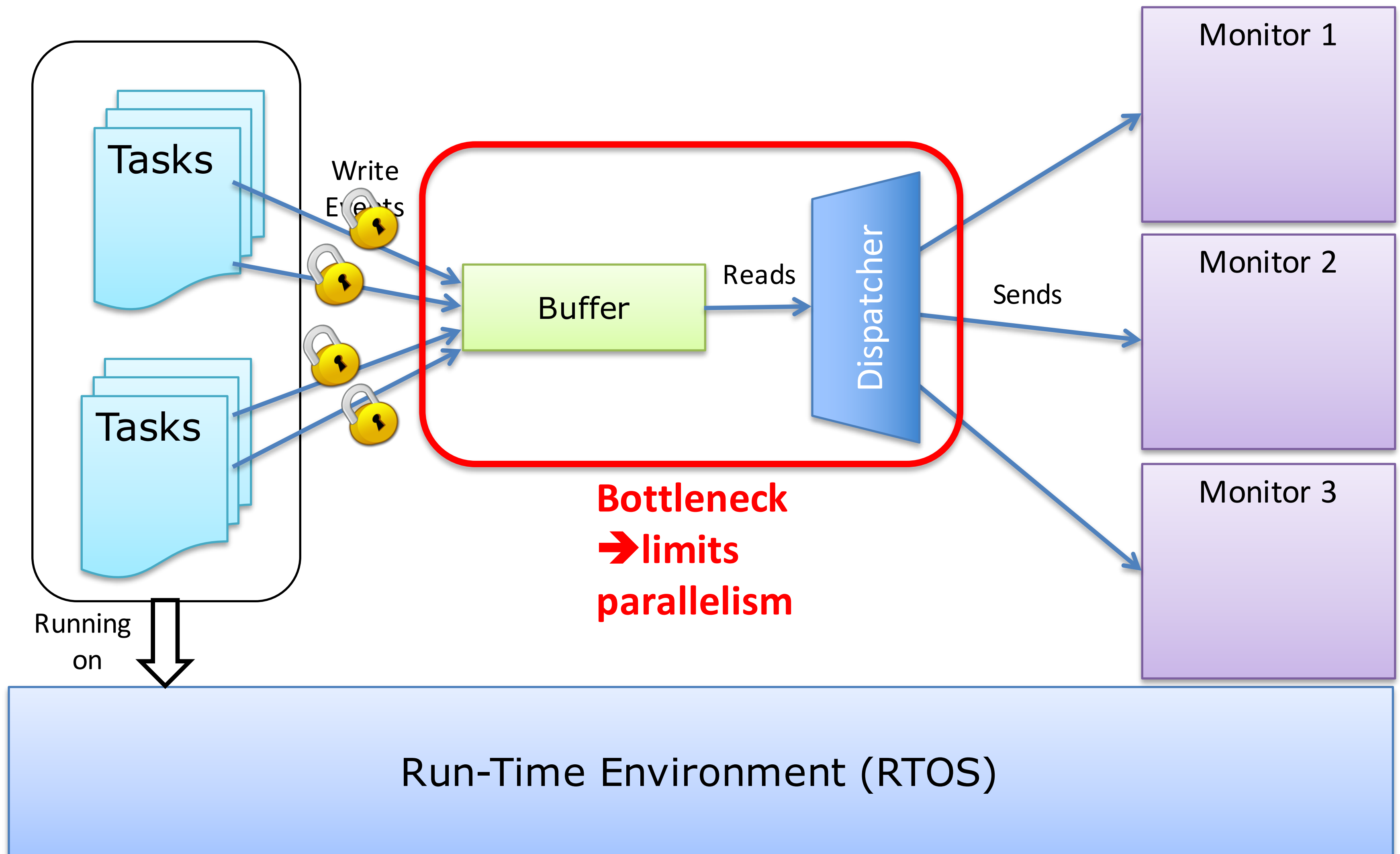
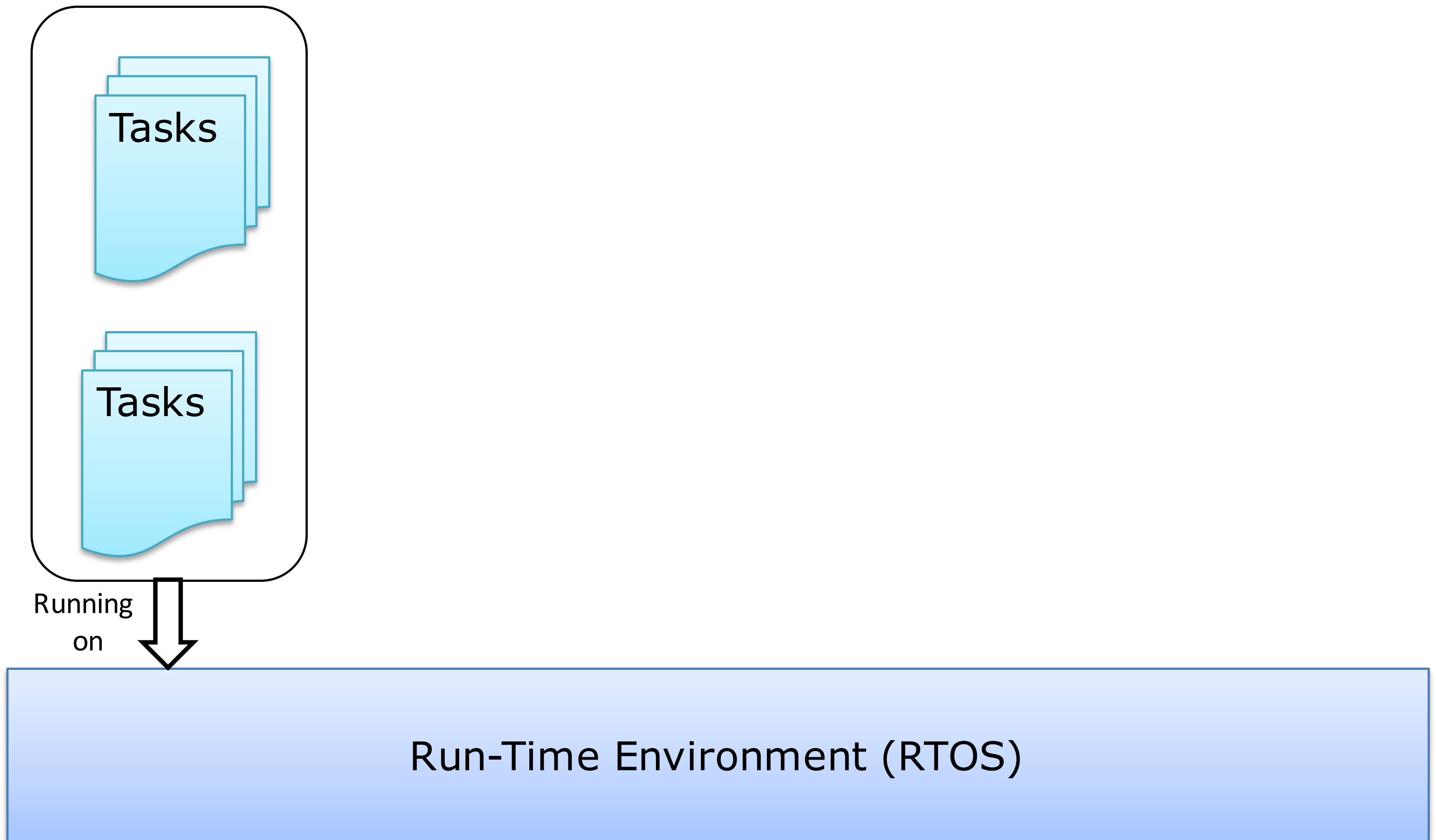


One Buffer per Monitor



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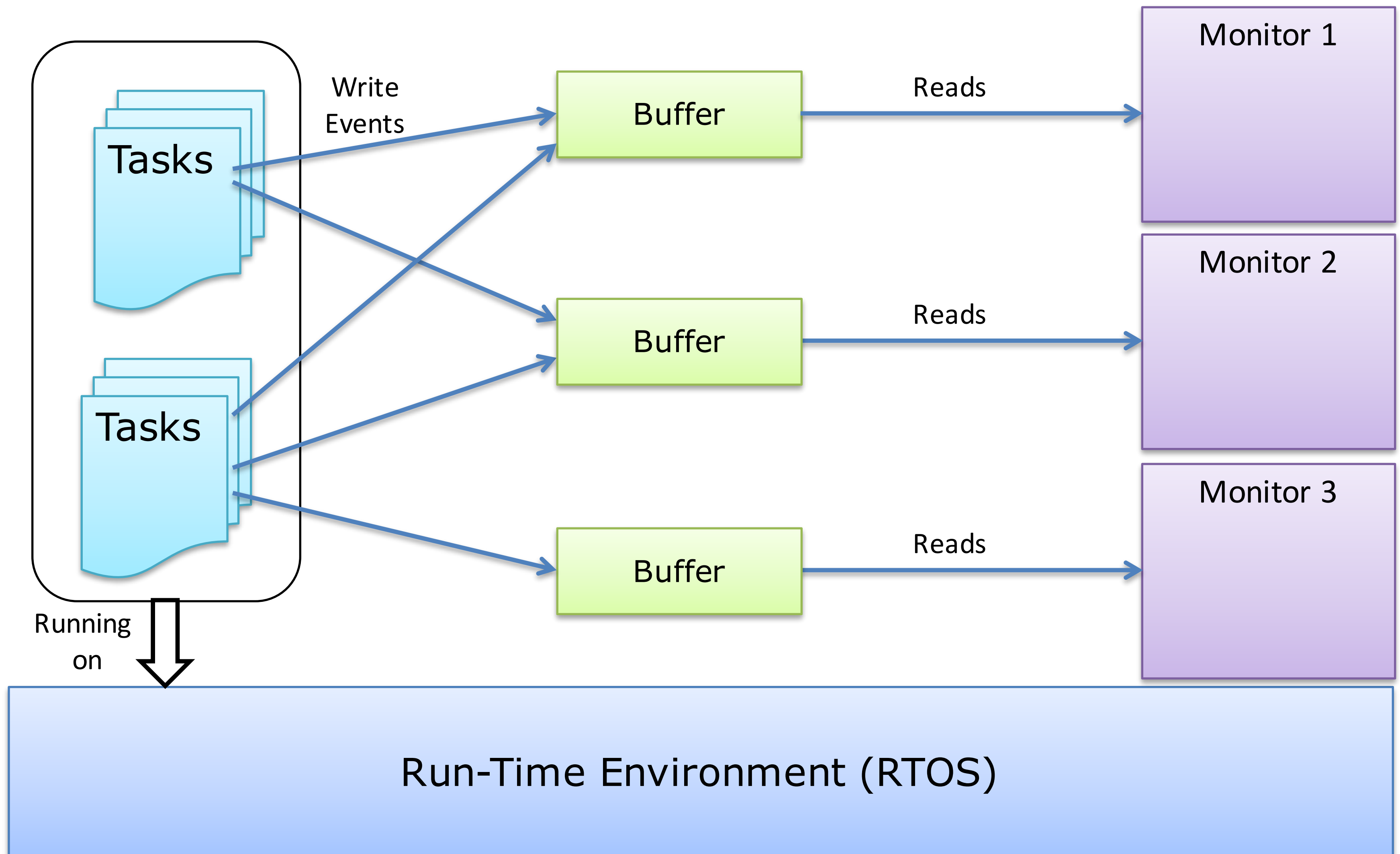

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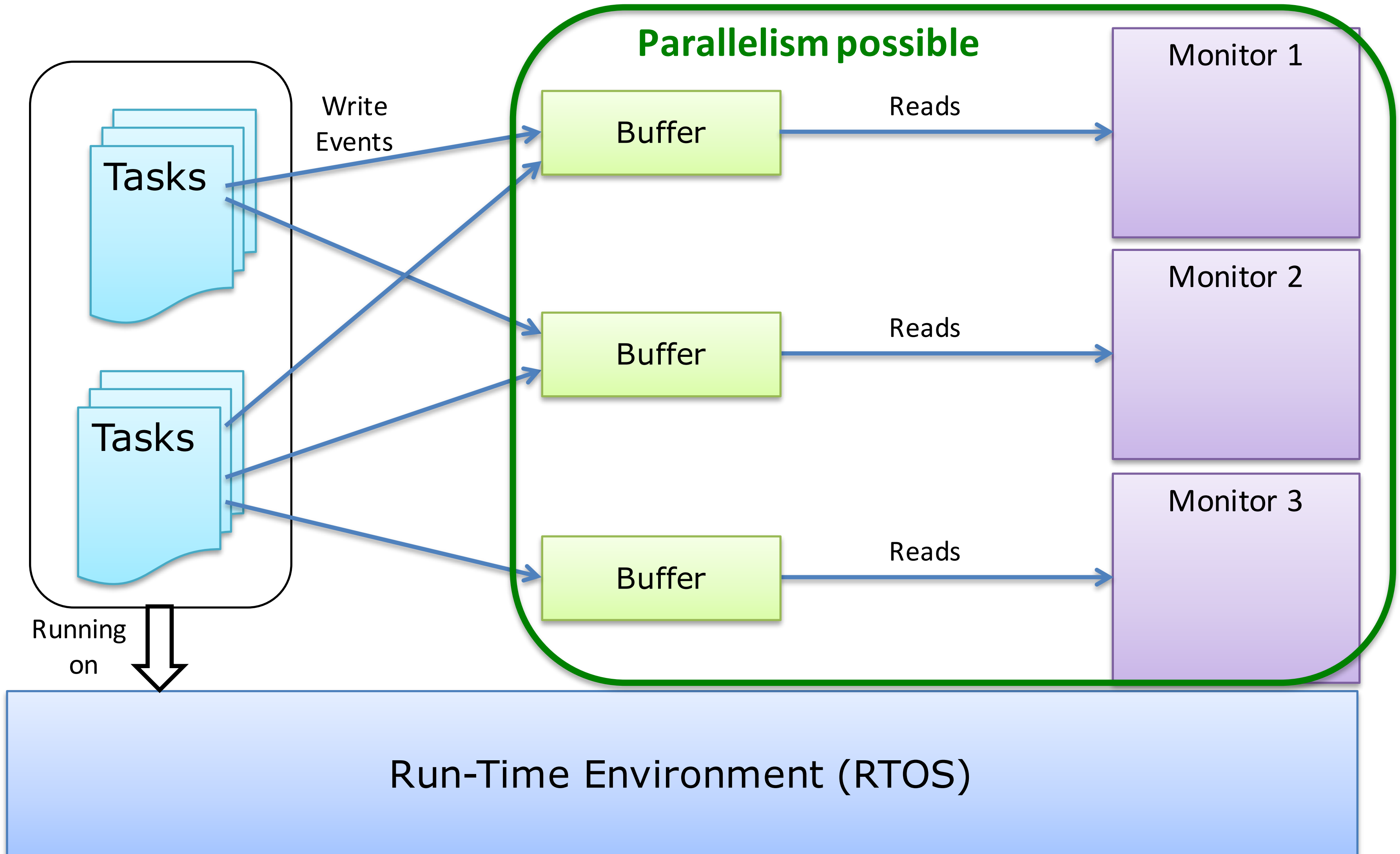

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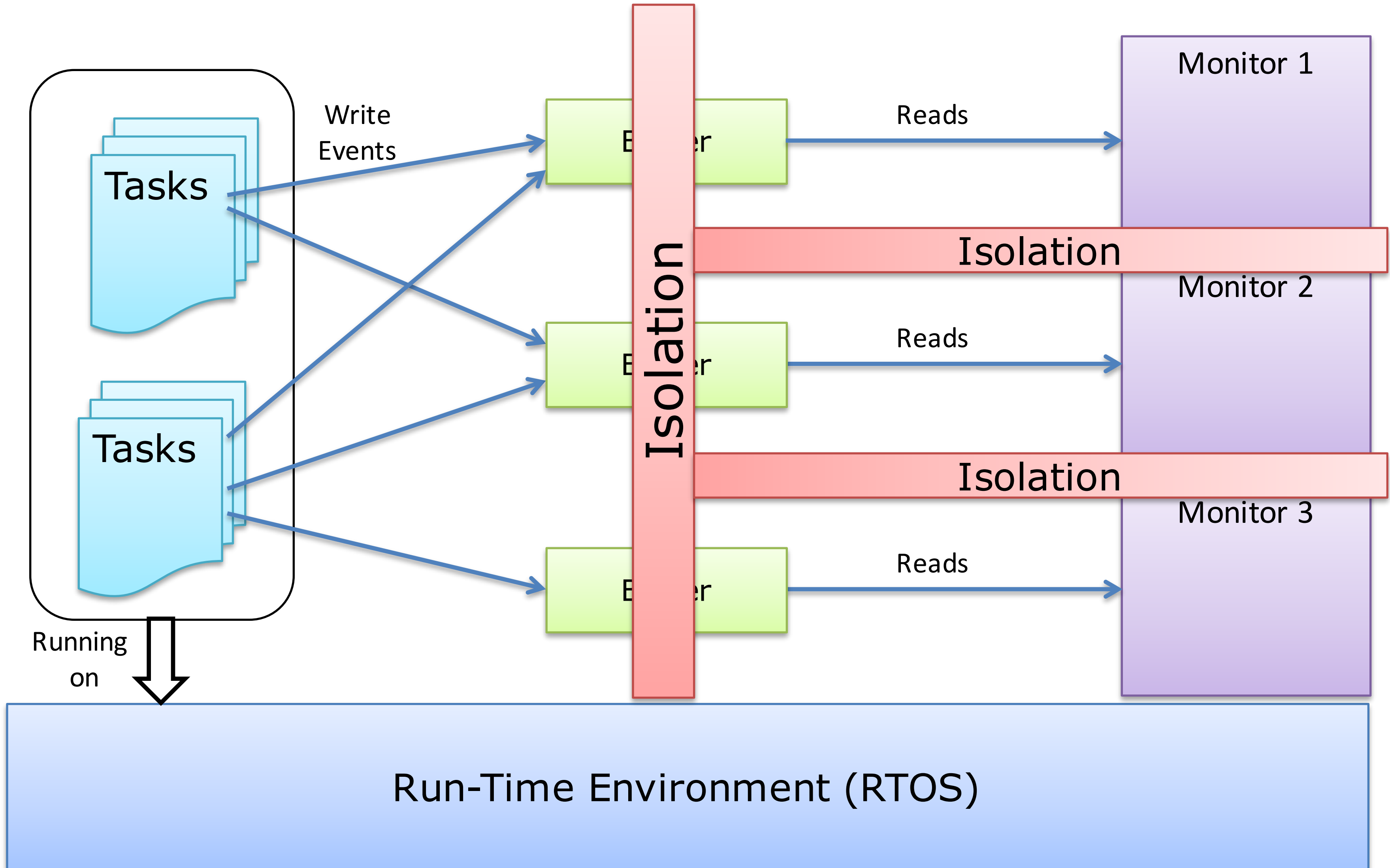

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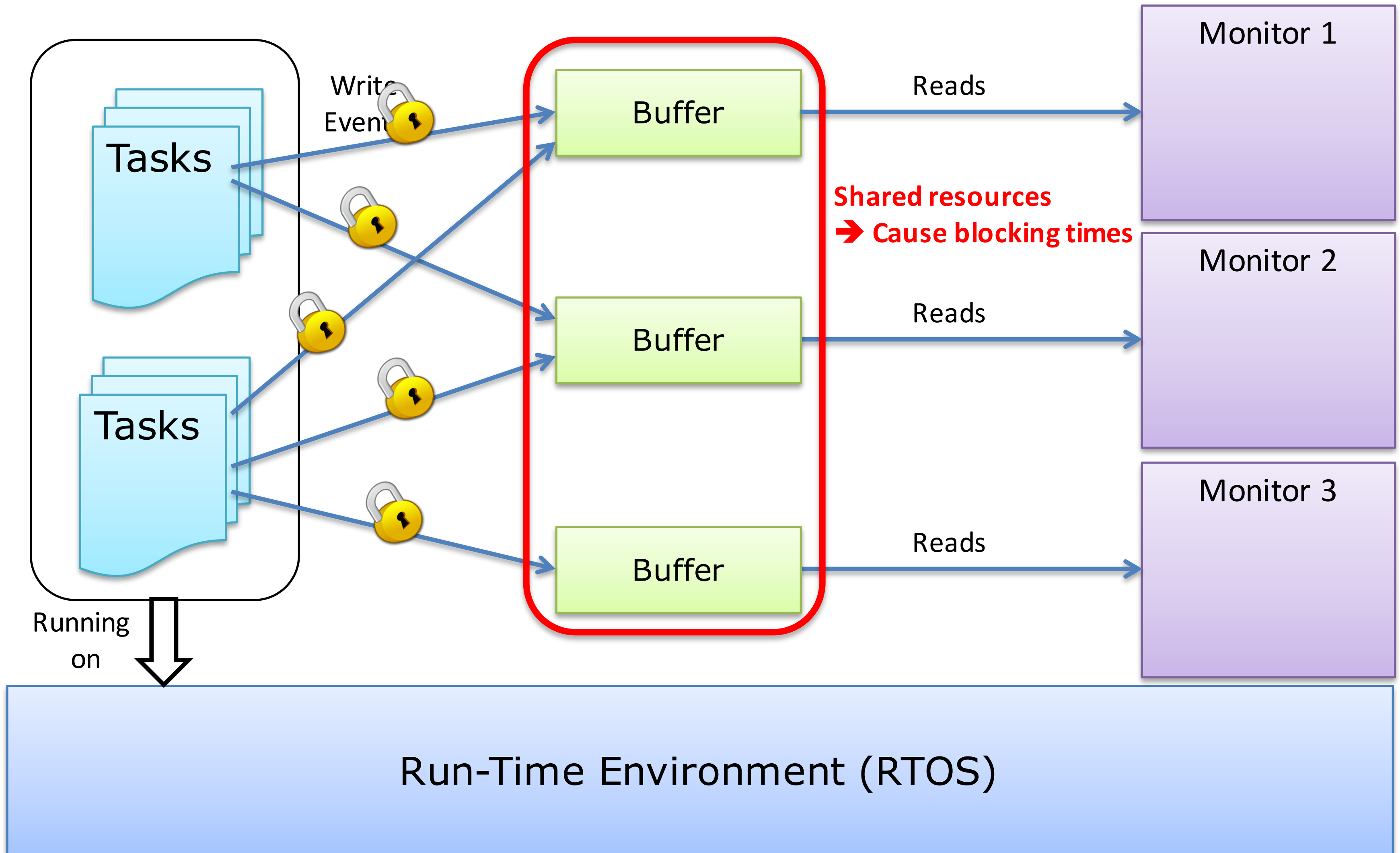

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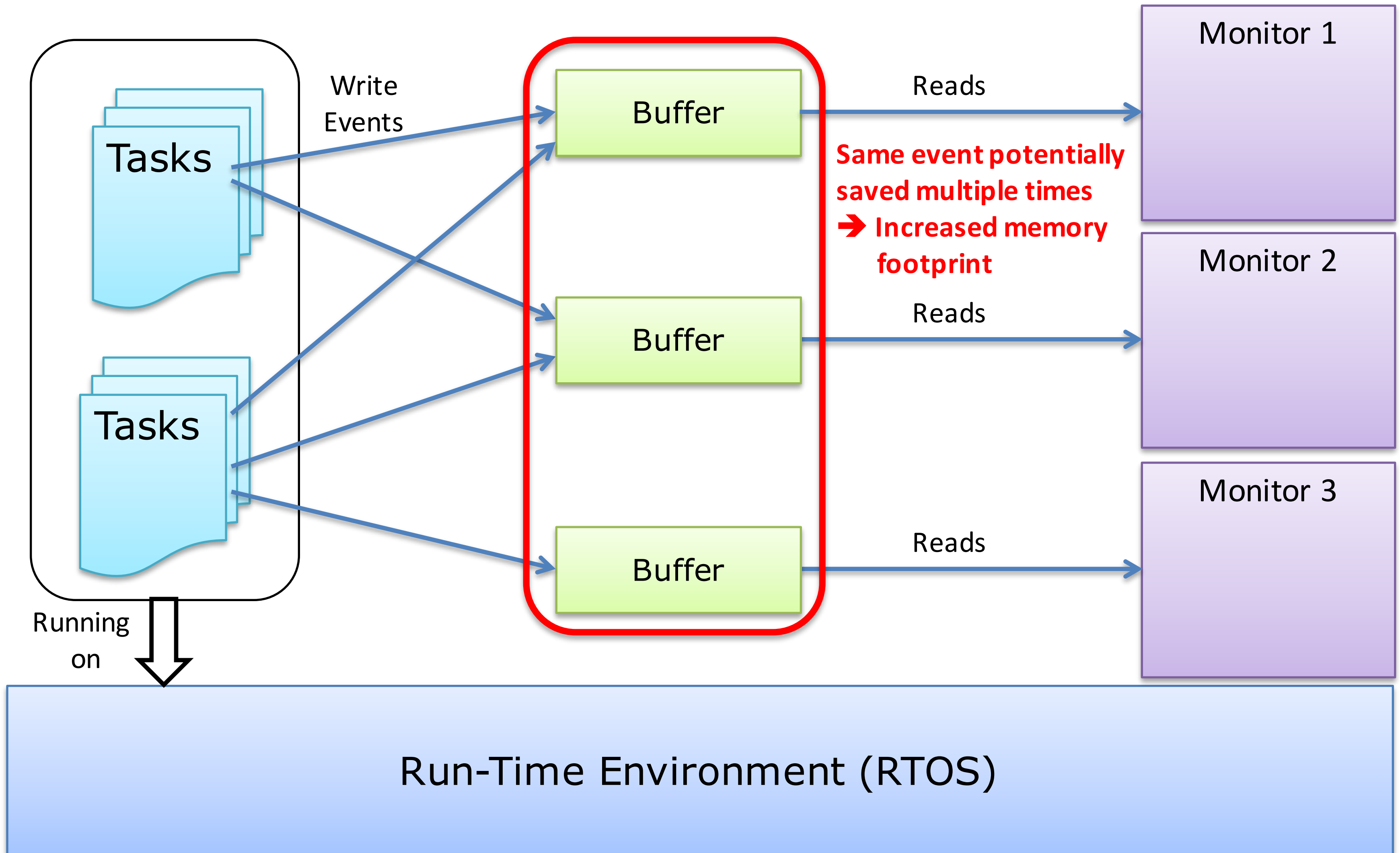
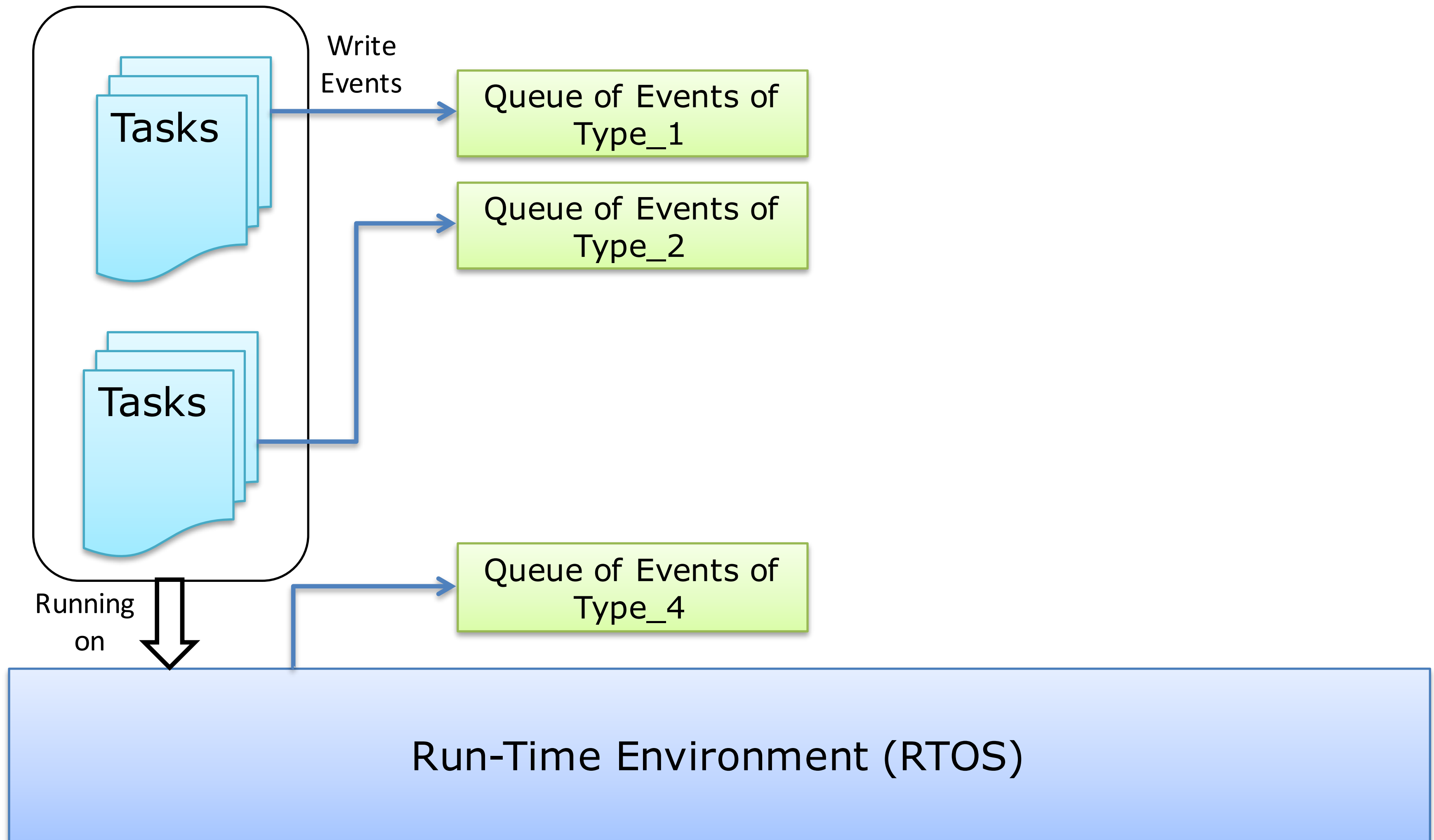


A NOVEL RUN-TIME MONITORING ARCHITECTURE

One Buffer per Event Type

One Buffer per Event Type



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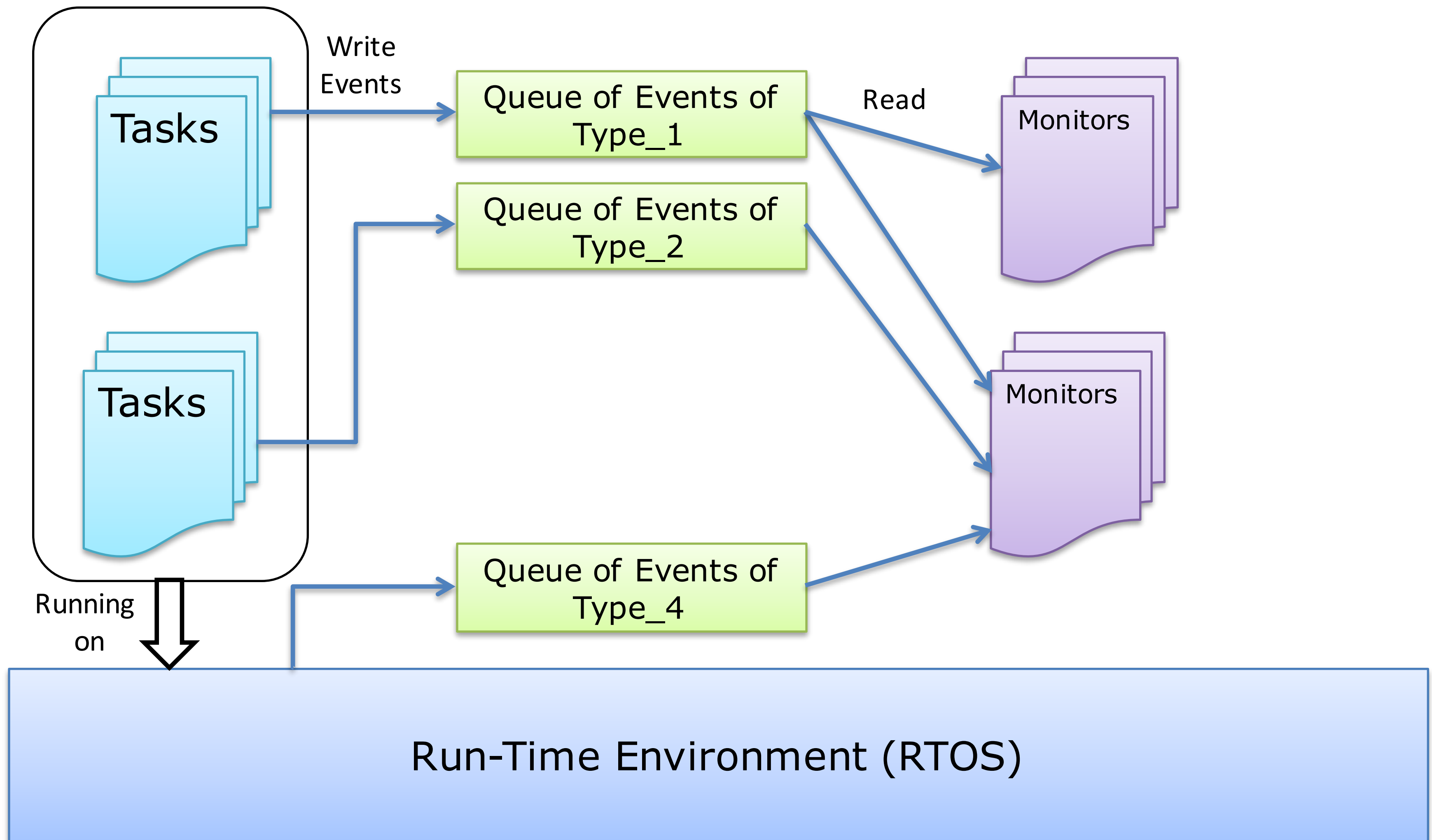

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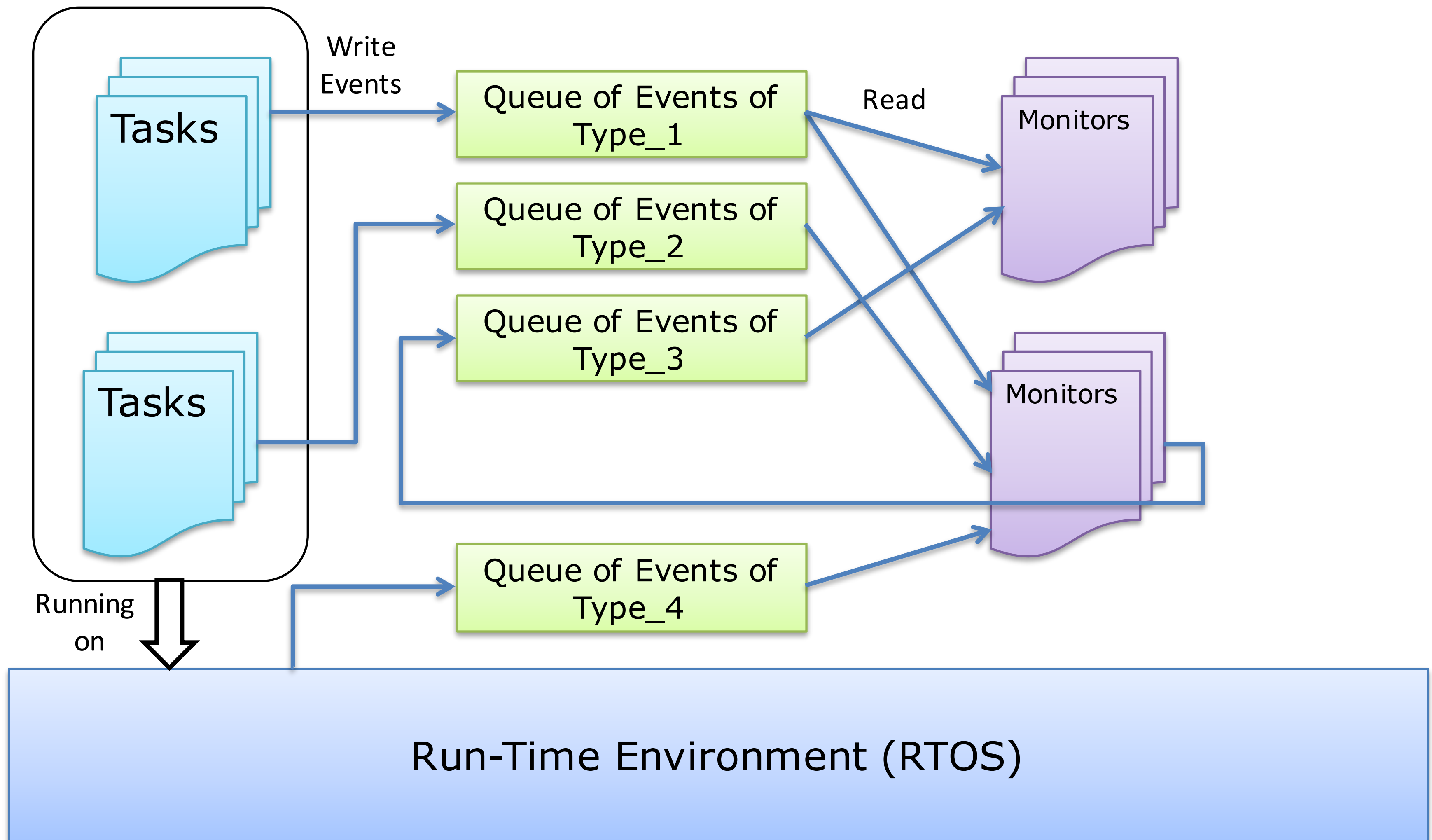

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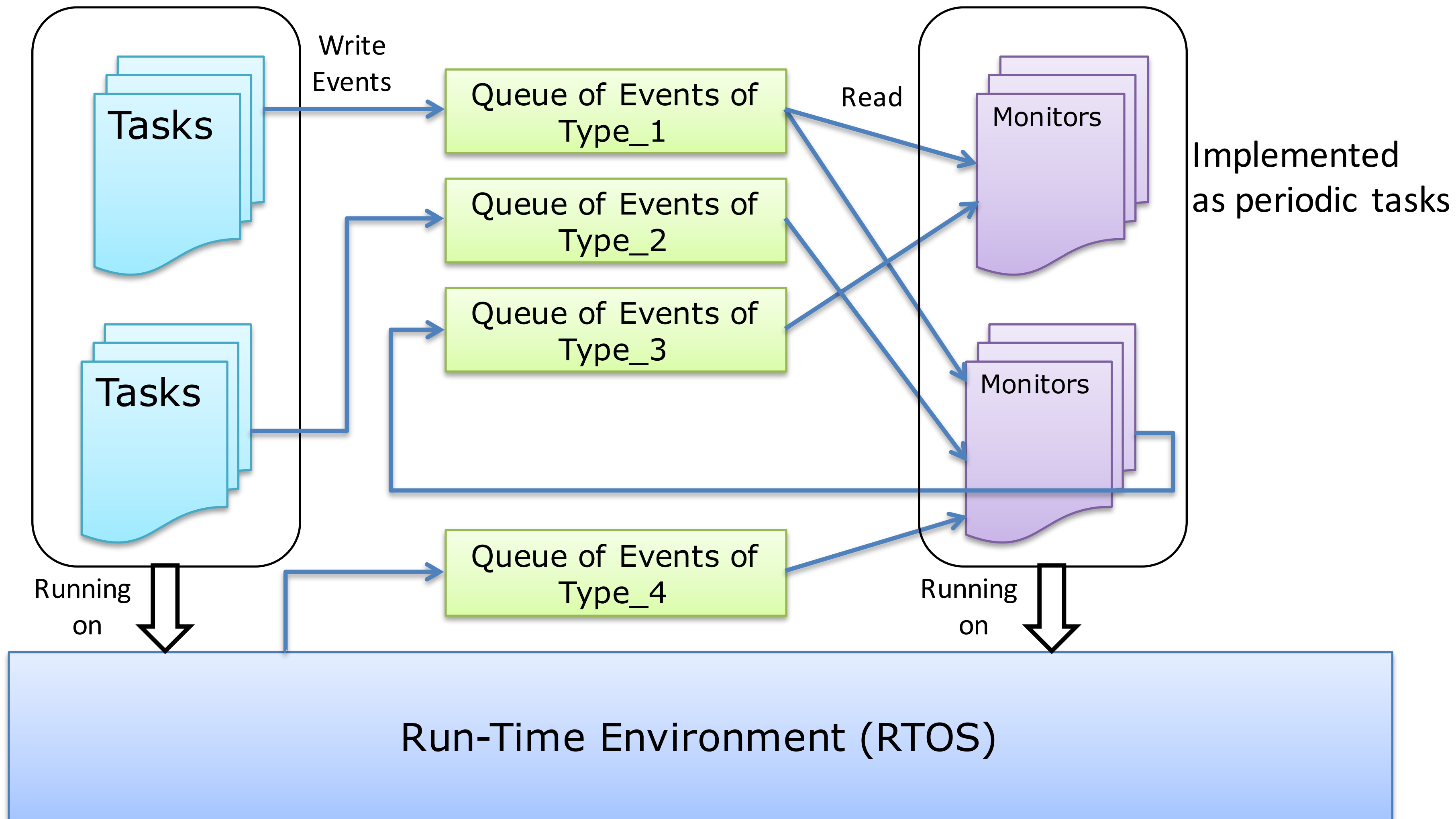

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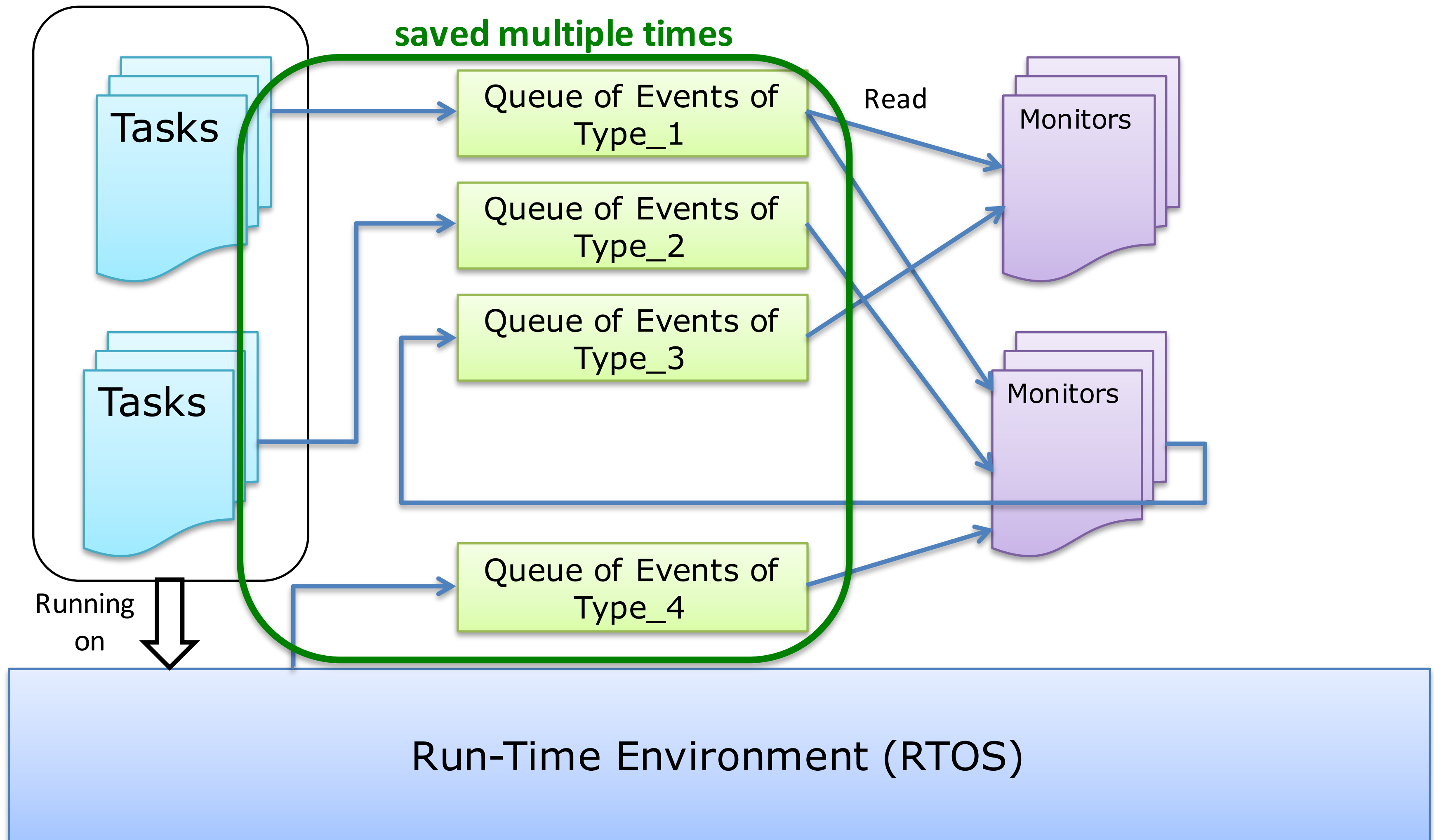

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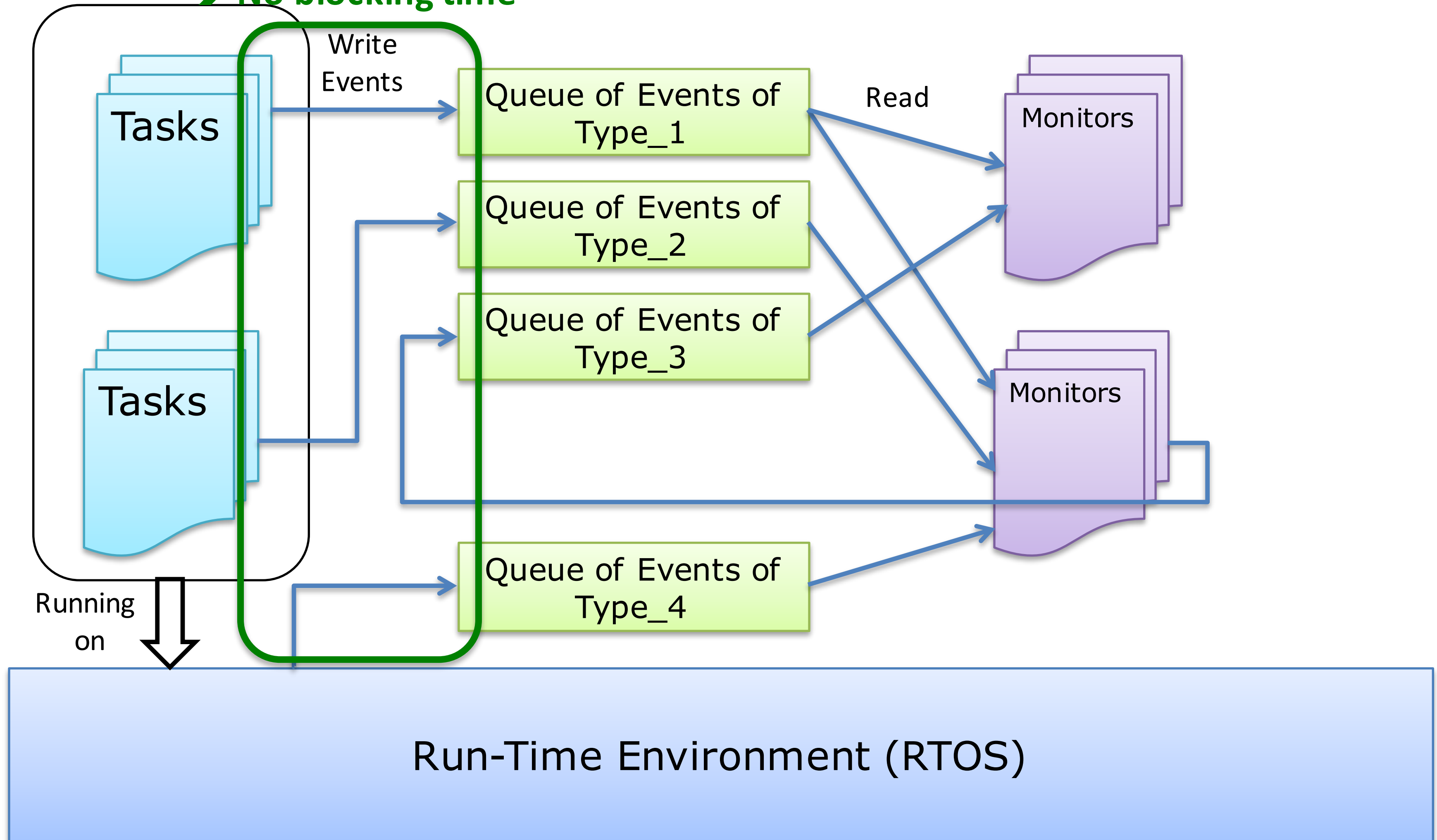

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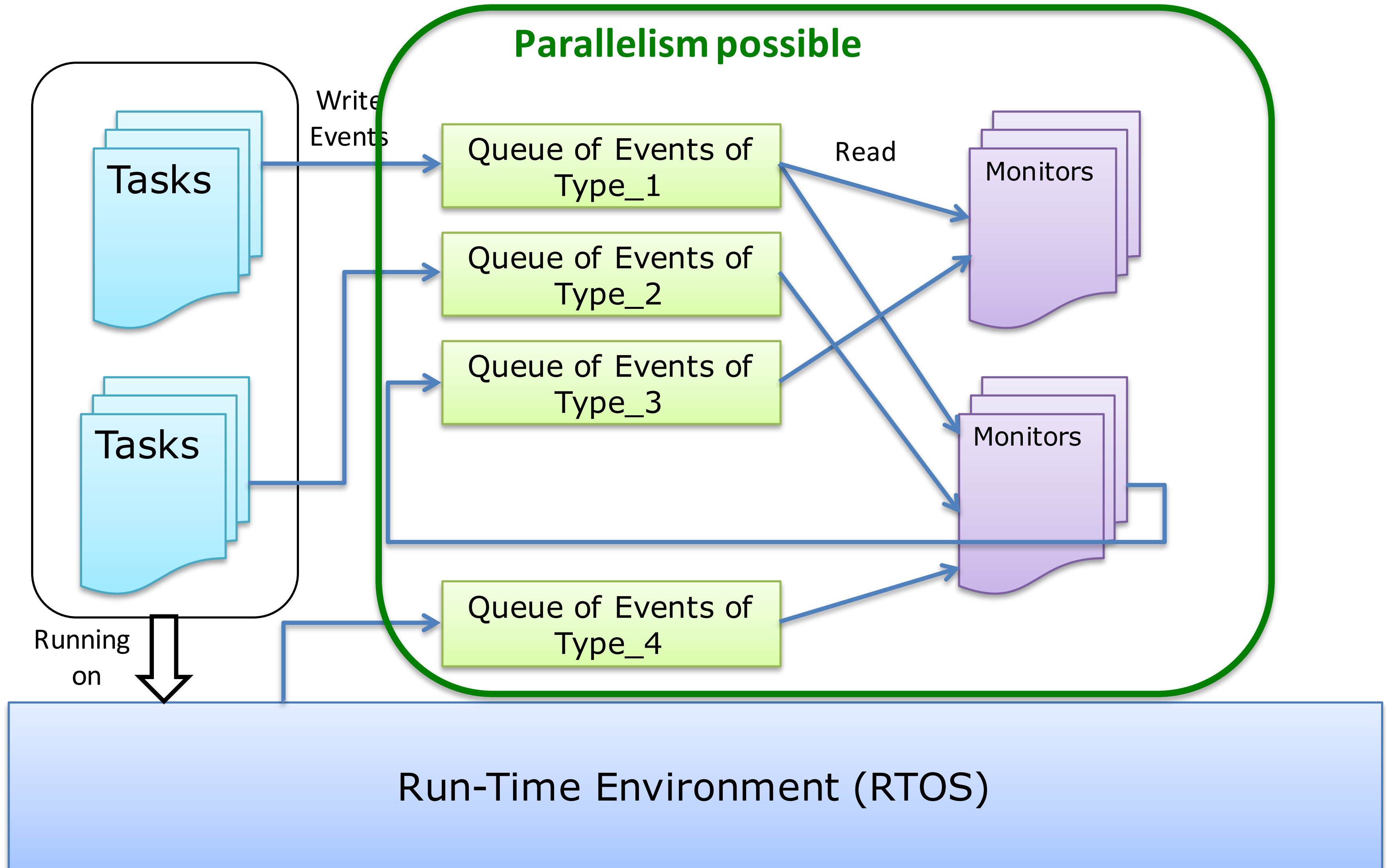

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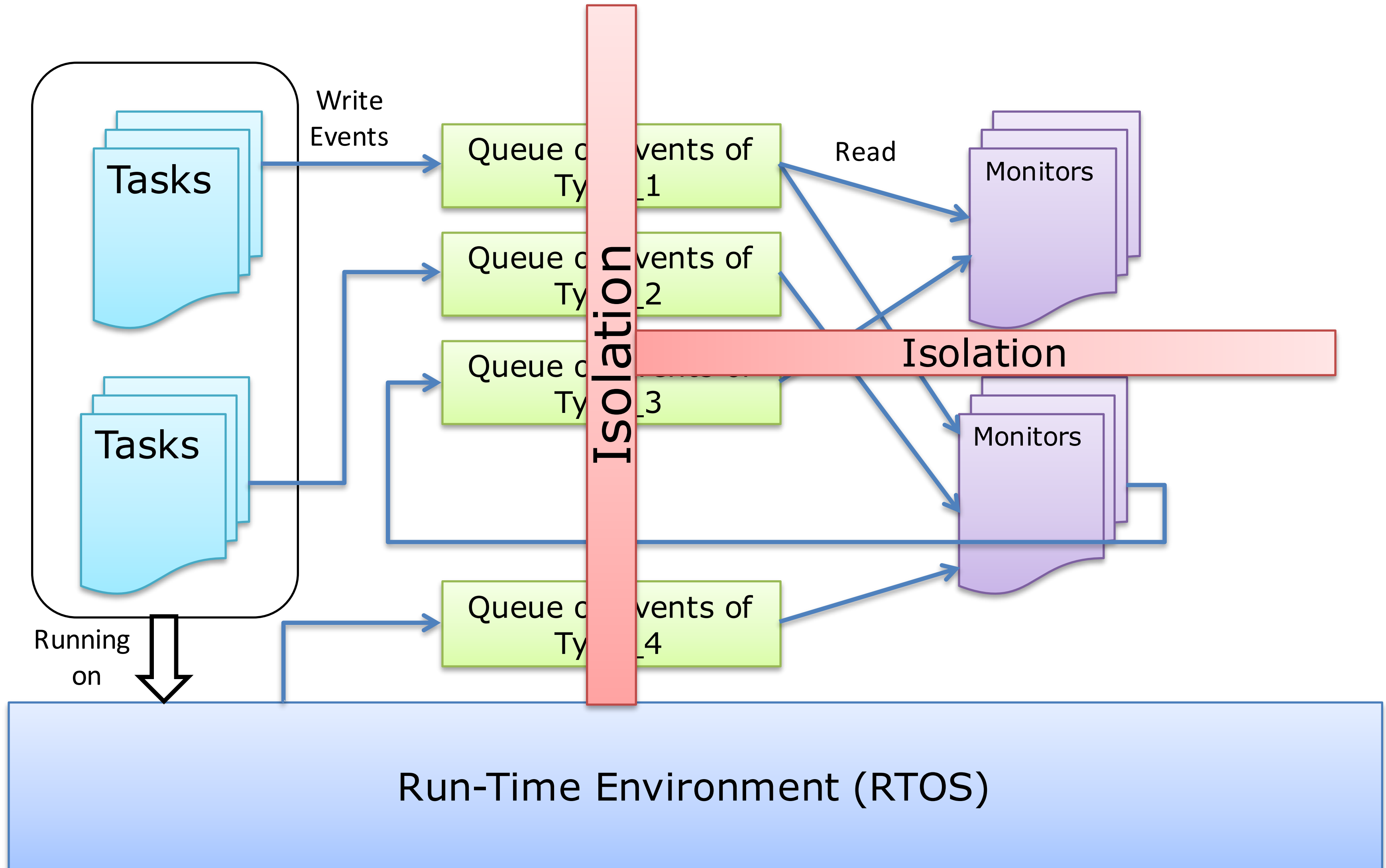

One Buffer per Event Type

- Events of different types used by a same monitor are not ordered
  - ➔The monitor must reorder them
  - ➔Does not require more reads than when there is only one buffer per monitor

One Buffer per Event Type

- If T_i is the period of the monitor, any error is detected in strictly less than

$$R_i = 2 \times T_i$$

➔The responsiveness can be configured

- Assuming the system is schedulable

A RUN-TIME VERIFICATION FRAMEWORK FOR REAL-TIME SYSTEMS

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  - ➔Difficult to prove their correctness
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How to Generate Monitors?

- Programming them **by hand**?
  - ➔ It may be complex to capture all possible cases
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- Solution: Rely on
  - high level formal specification languages
  - Correct-by-construction monitor generation

High-Level Formal Specification Language

- Several existing tools
  - Mac: extended version of regular expressions
  - Eagle, Hawk: temporal logic
  - RuleR: formal rule based system
  - Java-MOP: multi-language → regular expressions, temporal logic, rule based, finite state machines
  - …

An Example with Java-MOP using Regular Expressions

```
package mop;
import java.io.*;
import java.util.*;

SafeFileWriter(FileWriter f) {
        static int counter = 0;
        int writes = 0;

        event open after() returning(FileWriter f) :
                call(FileWriter.new(..)) {
                        this.writes = 0;
                }

        event write before(FileWriter f) :
                call(* write(..)) && target(f) {
                        this.writes ++;
                }

        event close after(FileWriter f) :
                 call(* close(..)) && target(f) {}
```

```
        ere : (open write* close)*

        @fail {
                System.out.println("write  after close");
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        }
        @match {
                System.out.println((++(counter))
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Name of the monitor

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Declaration of internal variables

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```

Declaration of the events used by the monitor

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event **open** generated after a call to FileWriter.new(..)

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Specification

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```

What must be done in case of respect or failure of the specification

```
	ere : (open write* close)*

	@fail {
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```

Can be used by existing tools (based on Aspect Oriented Programming) to automatically instrument the application code

```
	ere : (open write* close)*

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Can automatically be translated in a finite state machine.

And than in code implementing the monitor

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```

Limitations of Existing Tools

- Limited notion of time
  - E.g., impossible for MOP to check the execution time of a job, or the jitter on a release period
- Most expressive tools are extremely complex
  - E.g., possible to express exec. time and jitter with RuleR at the cost of multiple recursive rules
- Do not generate code for a monitoring architecture suited for safety-critical systems

➔ Unsuited to real-time safety critical systems

WORK IN PROGRESS

Work in Progress

- Design of a new specification language (Sangeeth)
  - Suited to real-time safety critical systems
  - Easy to use for engineers
- Automatic generation of complex automata that describe the monitor behaviour based on the specifications (Sangeeth)
- Automatic code-generation for monitors from the generated automata (Sonia and Vedanshi in IIIT-D)
- Integration of the monitoring architecture as a service in an RTOS which is ARINC compliant (Humberto)