Systems, Networks & Concurrency 2020

7

Safety & Liveness

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References for this chapter

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Chandy, K, Misra, Jayadev & Haas, Laura
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Transactions on Computer Systems (TOCS) 1983 vol. 1 (2)

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Silberschatz, Abraham, Galvin, Peter & Gagne, Greg
Operating System Concepts
John Wiley & Sons, Inc., 2001

Repetition

Correctness concepts in concurrent systems

Extended concepts of correctness in concurrent systems:

$\neg$ Termination is often not intended or even considered a failure

Safety properties:

$$(P(I) \wedge Processes(I,S)) \Rightarrow \Box Q(I,S)$$

where $\Box Q$ means that Q does *always* hold

Liveness properties:

$$(P(I) \wedge Processes(I,S)) \Rightarrow \Diamond Q(I,S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)
and S is the current state of the concurrent system

Repetition

Correctness concepts in concurrent systems

Liveness properties:

$$(P(I) \wedge Processes(I,S)) \Rightarrow \Diamond Q(I,S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)

Examples:

- Requests need to complete eventually.
- The state of the system needs to be displayed eventually.
- No part of the system is to be delayed forever (fairness).

☞ Interesting *liveness* properties can become very hard to proof

Fairness

Liveness properties:

$$(P(I) \land Processes(I,S)) \Rightarrow \Diamond Q(I,S)$$

where $\Diamond Q$ means that Q does *eventually* hold (and will then stay true)

Fairness (as a means to avoid starvation): Resources will be granted …

- **Weak fairness:** $\Diamond \Box R \Rightarrow \Diamond G$ … eventually, if a process requests continually.
- **Strong fairness:** $\Box \Diamond R \Rightarrow \Diamond G$ … eventually, if a process requests infinitely often.
- **Linear waiting:** $\Diamond R \Rightarrow \Diamond G$ … before any other process had the same resource granted more than once (common fairness in distributed systems).
- **First-in, first-out:** $\Diamond R \Rightarrow \Diamond G$ … before any other process which applied for the same resource at a later point in time (common fairness in single-node systems).

Revisiting

Correctness concepts in concurrent systems

Safety properties:

$$(P(I) \wedge Processes(I,S)) \Rightarrow \Box Q(I,S)$$

where $\Box Q$ means that Q does *always* hold

Examples:

- *Mutual exclusion* (no resource collisions) ☞ *has been addressed*
- *Absence of deadlocks* ☞ *to be addressed now*
  (and other forms of 'silent death' and 'freeze' conditions)
- *Specified responsiveness* or free capabilities ☞ *Real-time systems*
  (typical in real-time / embedded systems or server applications)

Deadlocks

Most forms of synchronization may lead to

Deadlocks

(Avoidance / prevention of deadlocks is one central safety property)

- ☞ How to predict them?
- ☞ How to find them?
- ☞ How to resolve them?
- ☞ … or are there structurally dead-lock free forms of synchronization?

Towards synchronization

Reserving resources in reverse order

```
var reserve_1, reserve_2 : semaphore := 1;
```

```
process P1;
  statement X;

  wait (reserve_1);
  wait (reserve_2);
    statement Y; -- employ all resources
  signal (reserve_2);
  signal (reserve_1);

  statement Z;
end P1;
```

```
process P2;
  statement A;

  wait (reserve_2);
  wait (reserve_1);
    statement B; -- employ all resources
  signal (reserve_1);
  signal (reserve_2);

  statement C;
end P2;
```

Sequence of operations: $A \rightharpoonup B \rightharpoonup C$; $X \rightharpoonup Y \rightharpoonup Z$; $[X,Z \mid A,B,C]$; $[A,C \mid X,Y,Z]$; $\neg[B \mid Y]$
or: $[A \mid X]$ followed by a deadlock situation.

Towards synchronization

Circular dependencies

```
var reserve_1, reserve_2, reserve_3 : semaphore := 1;
```

```
process P1;
  statement X;
  wait (reserve_1);
  wait (reserve_2);
    statement Y;
  signal (reserve_2);
  signal (reserve_1);
  statement Z;
end P1;
```

```
process P2;
  statement A;
  wait (reserve_2);
  wait (reserve_3);
    statement B;
  signal (reserve_3);
  signal (reserve_2);
  statement C;
end P2;
```

```
process P3;
  statement K;
  wait (reserve_3);
  wait (reserve_1);
    statement L;
  signal (reserve_1);
  signal (reserve_3);
  statement M;
end P3;
```

Sequence of operations: $A \rightharpoonup B \rightharpoonup C; X \rightharpoonup Y \rightharpoonup Z; K \rightharpoonup L \rightharpoonup M;$
$[X,Z \mid A,B,C \mid K,M]; [A,C \mid X,Y,Z \mid K,M]; [A,C \mid K,L,M \mid X,Z]; \neg[B \mid Y \mid L]$

or: $[A \mid X \mid K]$ followed by a deadlock situation.

Deadlocks

Necessary deadlock conditions:

1. **Mutual exclusion:**
   resources cannot be used simultaneously.

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   where every process waits for release of a resource by the next one.

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4. **Circular wait:** a ring list of processes exists,
   where every process waits for release of a resource by the next one.

☞ A system *may* become deadlocked, if *all* these conditions apply!

Deadlocks

Deadlock strategies:

- Ignorance & restart
  ☞ Kill or restart unresponsive processes, power-cycle the computer, …
- Deadlock detection & recovery
  ☞ find deadlocked processes and recover the system in a coordinated way
- Deadlock avoidance
  ☞ the resulting system state is checked before any resources are actually assigned
- Deadlock prevention
  ☞ the system prevents deadlocks by its structure

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

1. *Break* **Mutual exclusion**:

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

Deadlocks

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

1. *Break* **Mutual exclusion**:
   By replicating critical resources, mutual exclusion becomes un-necessary (only applicable in very specific cases).

2. *Break* **Hold and wait**:

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

Deadlock prevention

(*Remove* one of the four necessary deadlock conditions)

1. *Break* **Mutual exclusion**:
   By replicating critical resources, mutual exclusion becomes un-necessary (only applicable in very specific cases).
2. *Break* **Hold and wait**:
   Allocation of all required resources in one request.
   Processes can either hold *none* or *all* of their required resources.
3. *Introduce* **Pre-emption**: :

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

Deadlocks

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   Provide the additional infrastructure to allow for pre-emption of resources. Mind that resources cannot be pre-empted, if their states cannot be fully stored and recovered.

4. *Break* **Circular waits**:

Deadlocks

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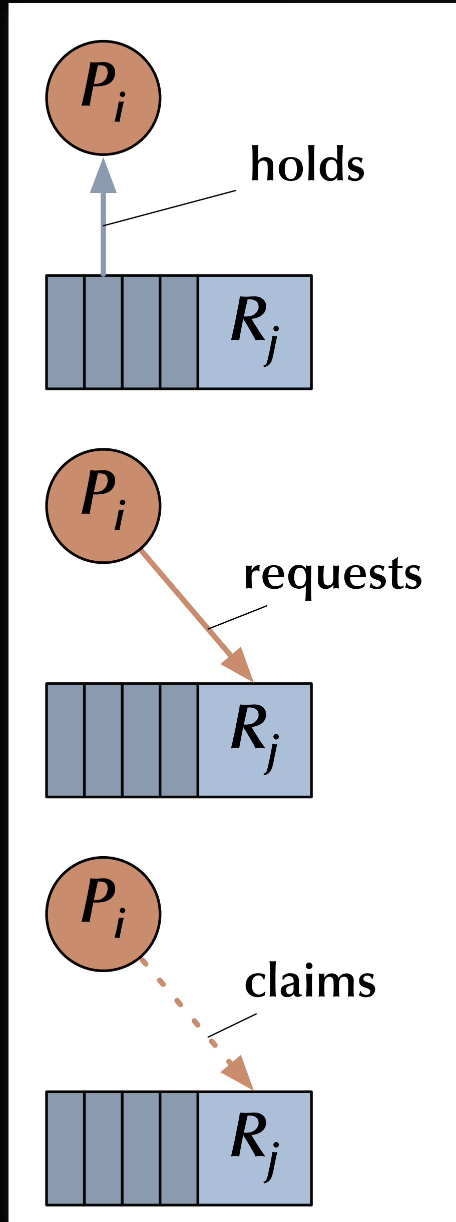
3. *Introduce* **Pre-emption**:
   Provide the additional infrastructure to allow for pre-emption of resources. Mind that resources cannot be pre-empted, if their states cannot be fully stored and recovered.
4. *Break* **Circular waits**:
   E.g. order all resources globally and restrict processes to request resources in that order only.

Mutual exclusion
Hold and wait
No pre-emption
Circular wait

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



$RAG = \{V, E\}$; Resource allocation graphs consist of vertices V and edges E.

$V = P \cup R$; Vertices V can be processes P or Resource types R.

with processes $P = \{P_1, \dots, P_n\}$
and resources types $R = \{R_1, \dots R_k\}$

$E = E_c \cup E_r \cup E_a$; Edges E can be "claims" E_c, "requests" E_r or "assignments" E_a

with claims $E_c = \{P_i \rightarrow R_j, \dots\}$
requests $E_r = \{P_i \rightarrow R_j, \dots\}$
and assignments $E_a = \{R_j \rightarrow P_i, \dots\}$

Note: any resource type R_j can have more than one instance of a resource.

Deadlocks

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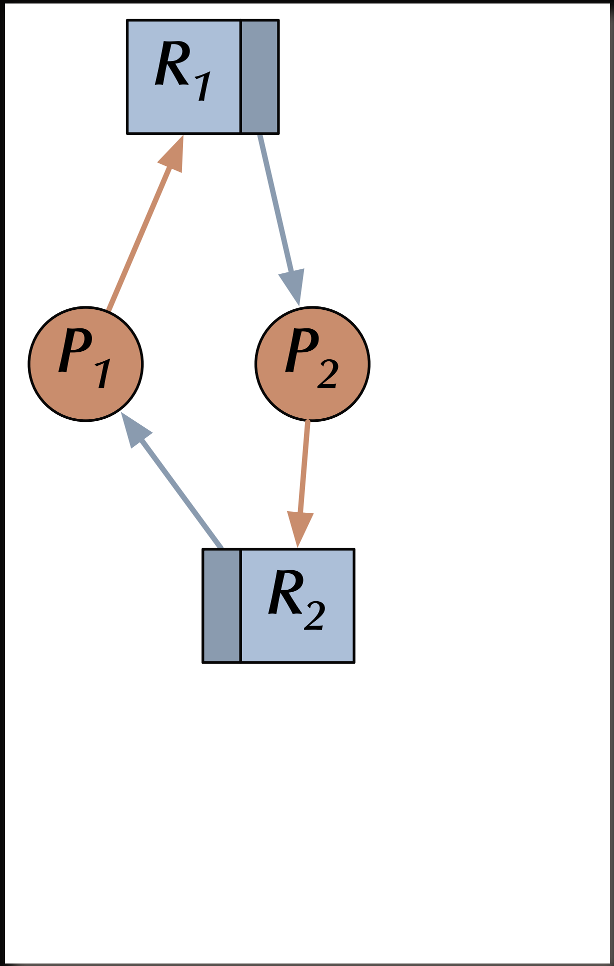
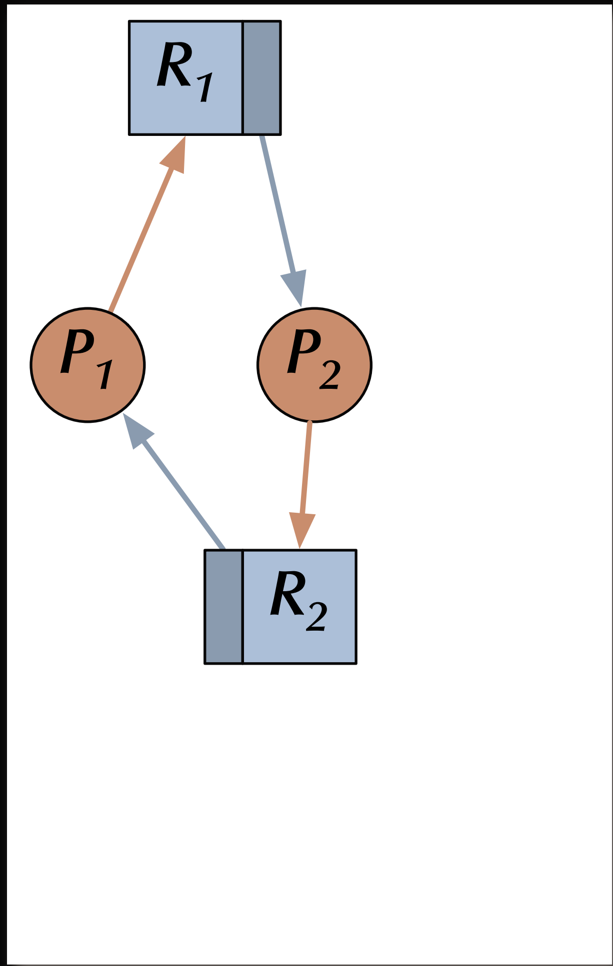


Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ Two process, reverse allocation deadlock:



Deadlocks

Resource Allocation Graphs

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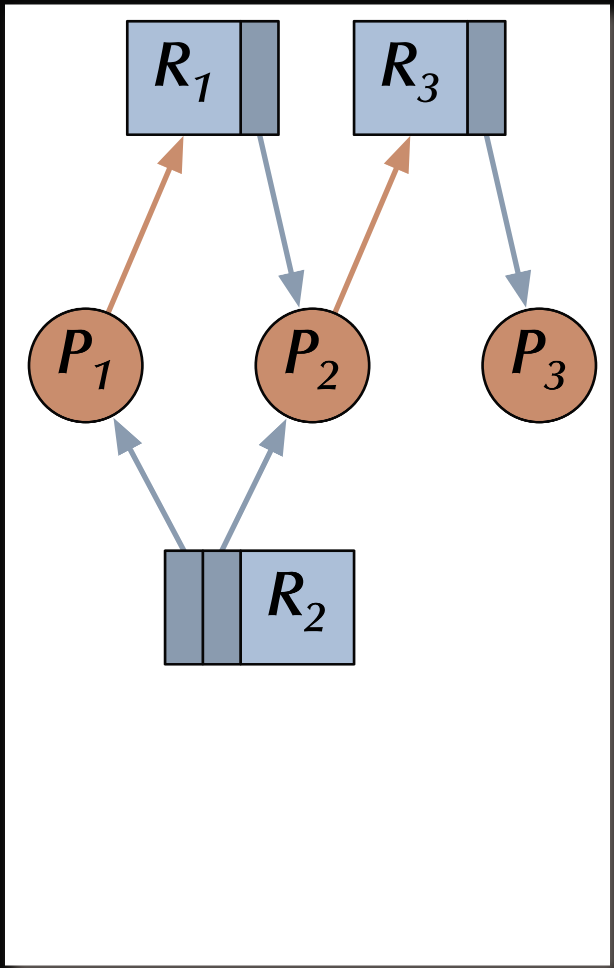

Deadlocks

Resource Allocation Graphs

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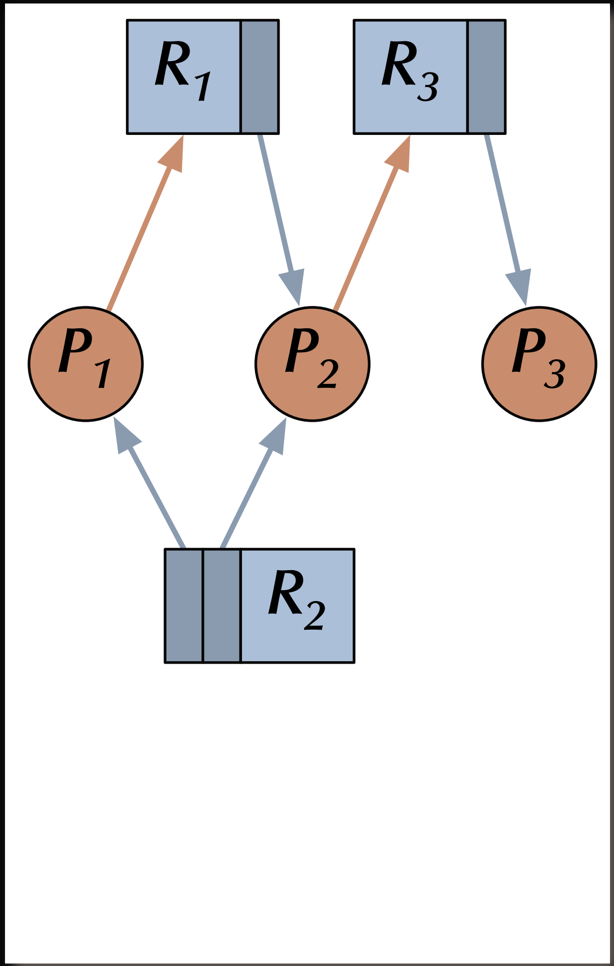
☞ No circular dependency ☞ no deadlock:



Deadlocks

Resource Allocation Graphs

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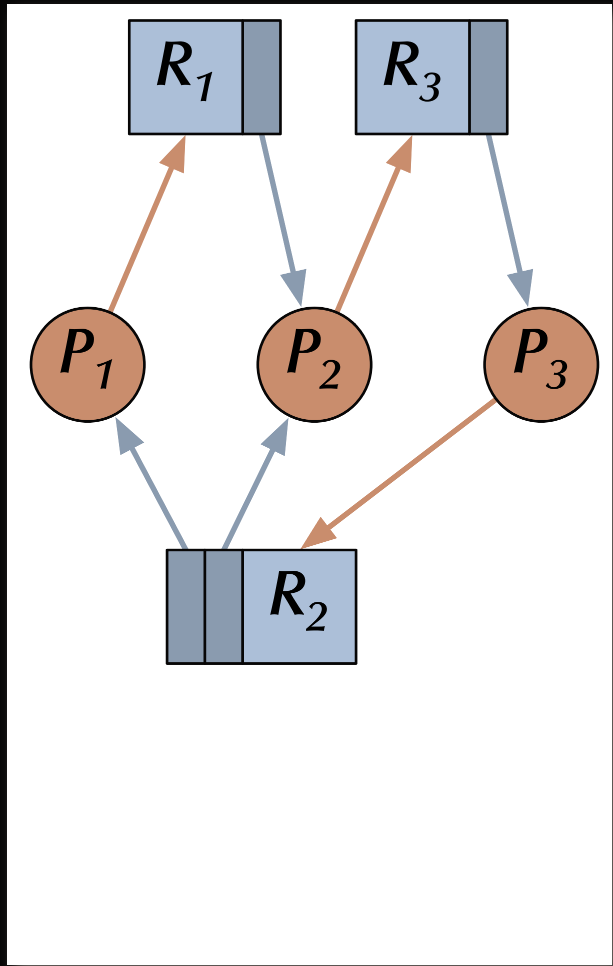

Deadlocks

Resource Allocation Graphs

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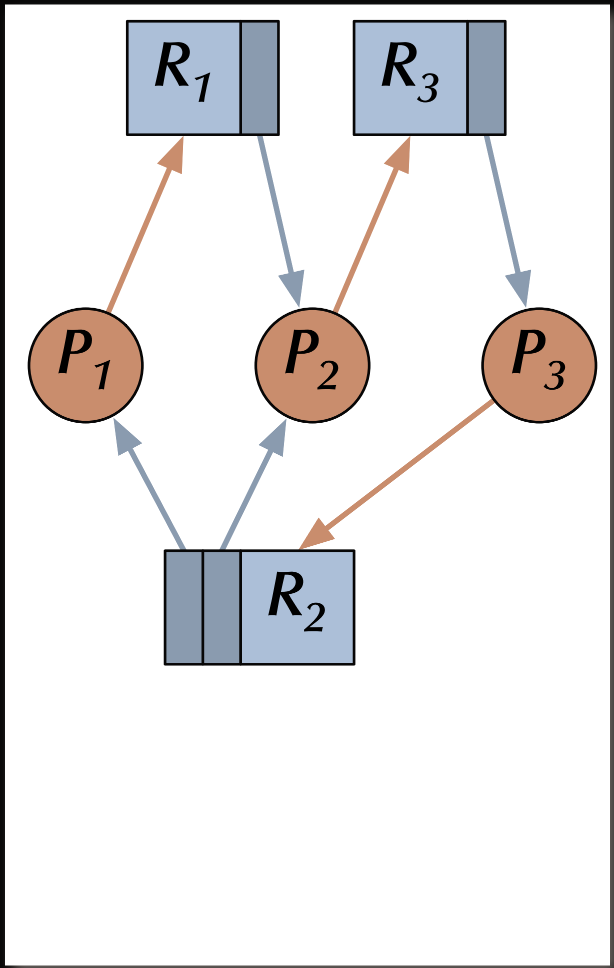


☞ Two circular dependencies ☞ deadlock:

$P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$

as well as: $P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

Derived rule:
If some processes are deadlocked **then** there are cycles in the resource allocation graph.

Deadlocks

Edge Chasing

(for the distributed version see Chandy, Misra & Haas)

∀ blocking processes:

☞ Send a probe to all requested yet unassigned resources containing ids of: [the blocked, the sending, the targeted node].

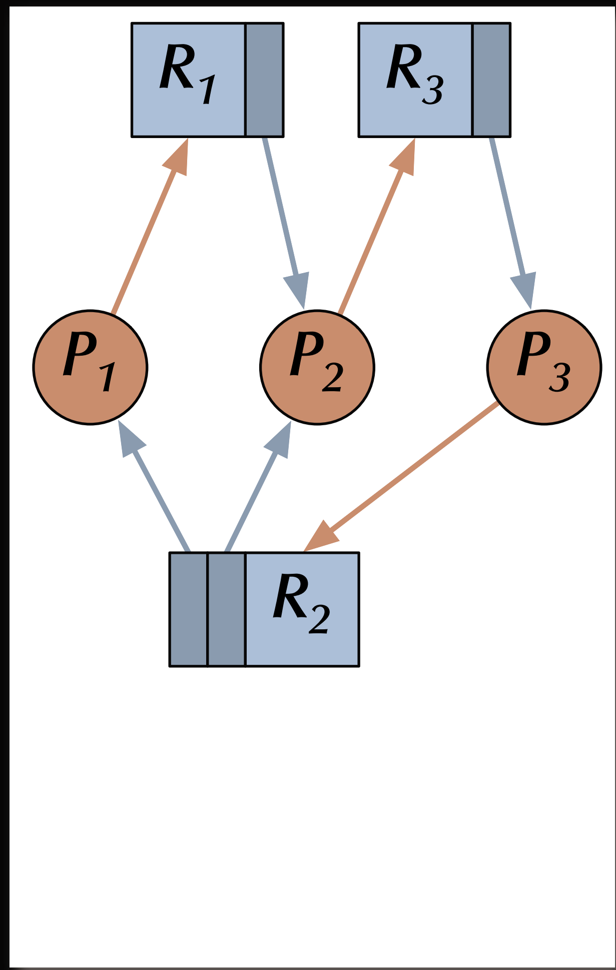
∀ nodes on probe reception:

☞ Propagate the probe to all processes holding the critical resources or to all requested yet unassigned resources – while updating the second and third entry in the probe.

∃ a process receiving its own probe:

(blocked-id = targeted-id)

☞ *Circular dependency detected.*



Deadlocks

Resource Allocation Graphs

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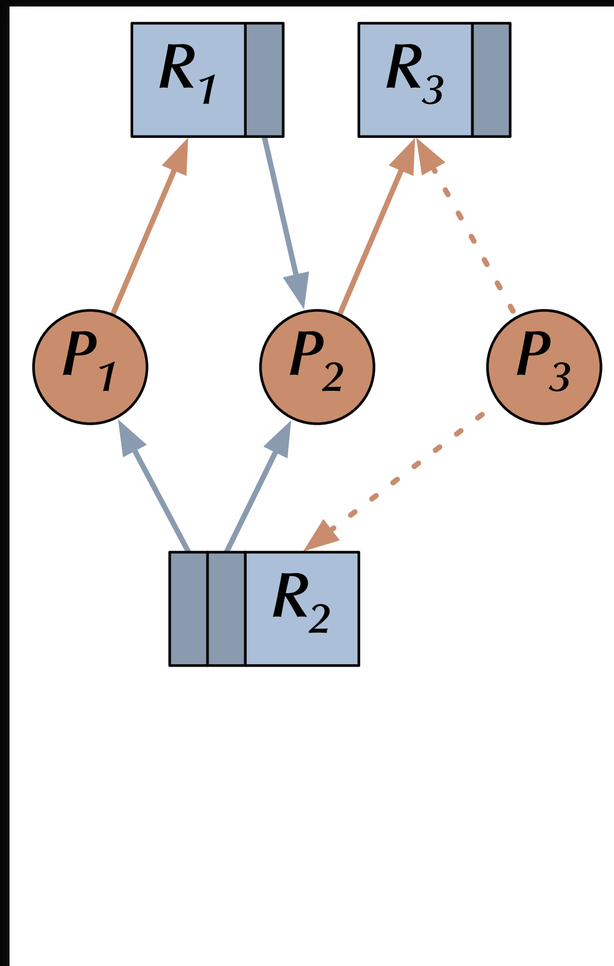


☞ Knowledge of claims:

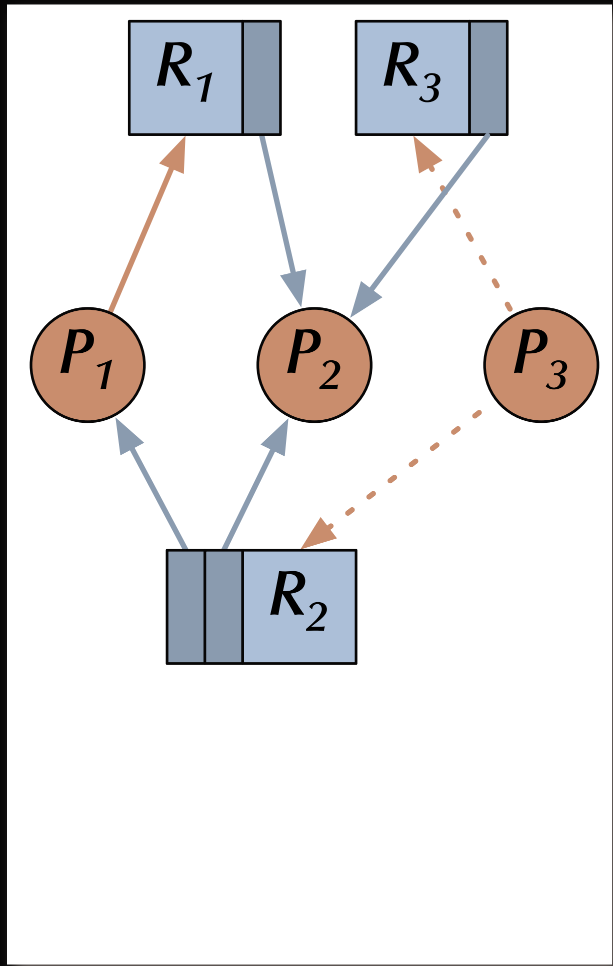
Claims are potential future requests which have no blocking effect on the claiming process – while actual *requests* are blocking.

Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

☞ Assignment of resources such that circular dependencies are avoided:



Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Earlier derived rule:

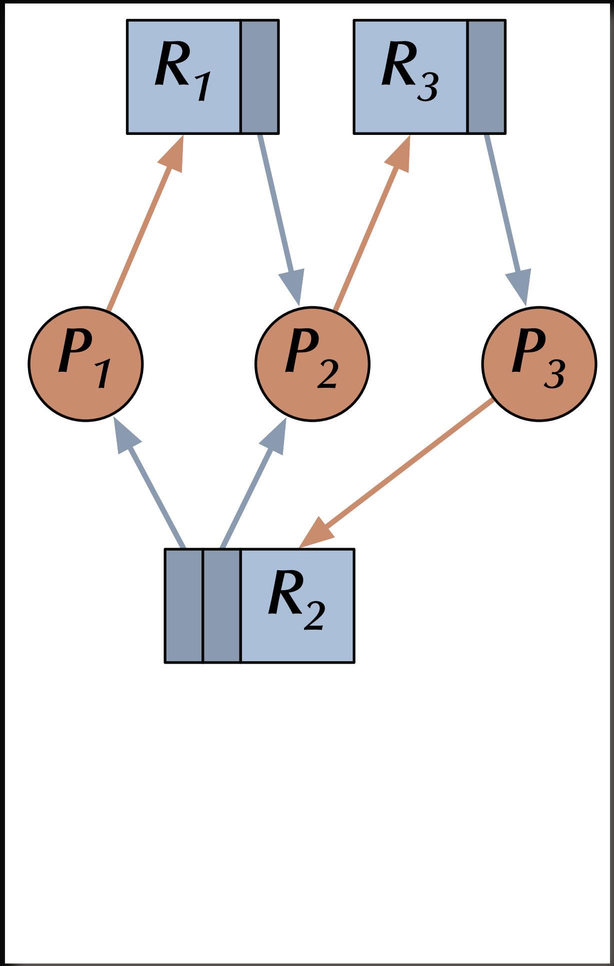
If some processes are deadlocked
then there are cycles in the resource allocation graph.

☞ Reverse rule for multiple instances:

If there are cycles in the resource allocation graph
and there are *multiple* instances per resource
then the involved processes are *potentially* deadlocked.

☞ Reverse rule for single instances:

If there are cycles in the resource allocation graph
and there is *exactly one* instance per resource
then the involved processes are deadlocked.



Deadlocks

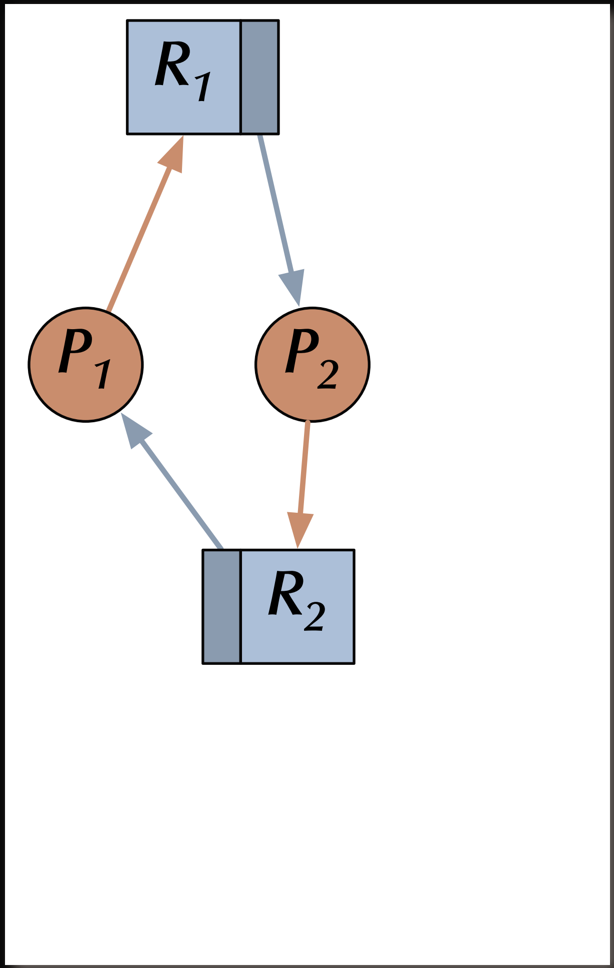
Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Reverse rule for single instances:

If there are cycles in the resource allocation graph
and there is *exactly one* instance per resource
then the involved processes are deadlocked.

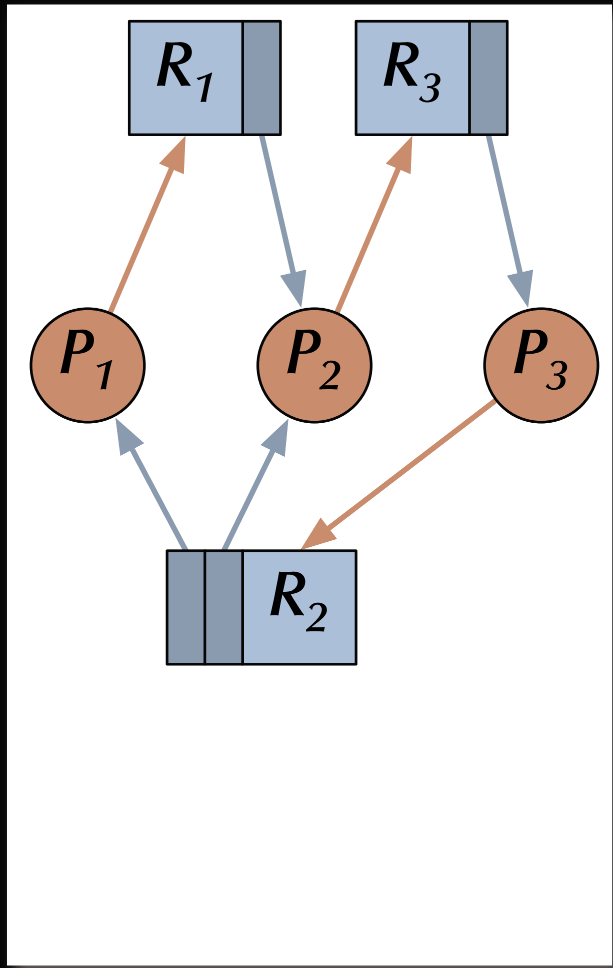
☞ Actual deadlock identified



Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)



Reverse rule for multiple instances:

If there are cycles in the resource allocation graph
and there are *multiple* instances per resource
then the involved processes are *potentially* deadlocked.

☞ Potential deadlock identified

Deadlocks

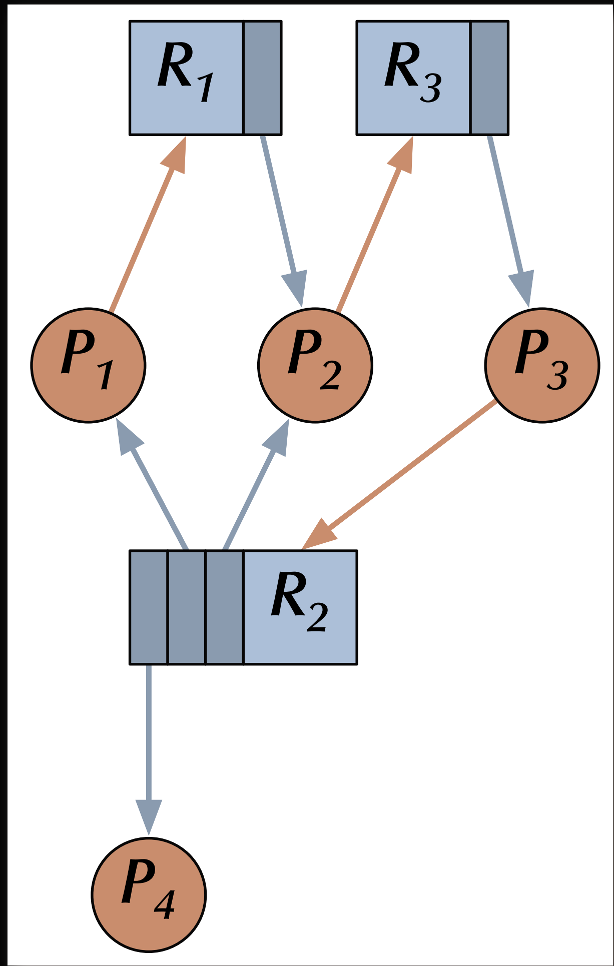
Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

Reverse rule for multiple instances:

If there are cycles in the resource allocation graph
and there are *multiple* instances per resource
then the involved processes are *potentially* deadlocked.

☞ Potential deadlock identified
– yet clearly not an actual deadlock here



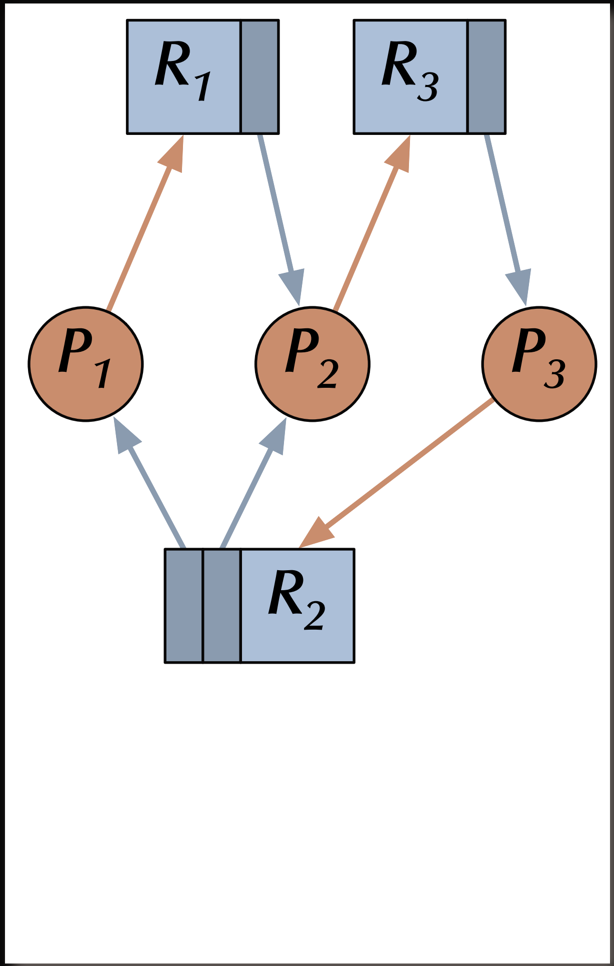
Deadlocks

Resource Allocation Graphs

(Silberschatz, Galvin & Gagne)

How to detect actual deadlocks in the general case?

(multiple instances per resource)



Deadlocks

Banker's Algorithm

There are processes $P_i \in \{P_1, \ldots, P_n\}$ and resource types $R_j \in \{R_1, \ldots, R_m\}$ and data structures:

- `Allocated [i, j]`

  ☞ the number of resources of type `j` *currently* allocated to process `i`.

- `Free [j]`

  ☞ the number of *currently* available resources of type `j`.

- `Claimed [i, j]`

  ☞ the number of resources of type `j` required by process `i` *eventually*.

- `Requested [i, j]`

  ☞ the number of *currently* requested resources of type `j` by process `i`.

- `Completed [i]`

  ☞ boolean vector indicating processes which may complete.

- `Simulated_Free [j]`

☞ Number of available resources assuming that complete processes deallocate their resources.

Deadlocks

Banker's Algorithm

1. Simulated_Free ⇐ Free; ∀i: Completed [i] ⇐ False;

2. **While** ∃i: ¬Completed [i]
   and ∀j: Requested [i, j] < Simulated_Free [j] **do**:

   ∀j: Simulated_Free [j] ⇐ Simulated_Free [j] + Allocated [i, j];
   Completed [i] ⇐ True;

3. **If** ∀i: Completed [i] **then** the system is currently **deadlock-free!**
   else all processes i with ¬Completed [i] are involved in a **deadlock!**.

Deadlocks

Banker's Algorithm

1. Simulated_Free ⇐ Free; ∀i: Completed [i] ⇐ False;

2. **While** ∃i: ¬Completed [i]
   and ∀j: Claimed [i, j] < Simulated_Free [j] **do**:

   ∀j: Simulated_Free [j] ⇐ Simulated_Free [j] + Allocated [i, j];
   Completed [i] ⇐ True;

3. **If** ∀i: Completed [i] **then** the system is **safe!**

A **safe** system is a system in which future deadlocks can be avoided assuming the current set of available resources.

Deadlocks

Banker's Algorithm

Check potential future system safety by simulating a granted request:
(**Deadlock avoidance**)

```
if (Request < Claimed) and (Request < Free) then
   Free      := Free      - Request;
   Claimed   := Claimed   - Request;
   Allocated := Allocated + Request;

   if System_is_safe (checked by e.g. Banker's algorithm) then

                                 ☞ Grant request

   else

             ☞ Restore former system state: (Free, Claimed, Allocated)

   end if;
end if;
```


Deadlocks

Distributed deadlock detection

Observation: Deadlock detection methods like Banker's Algorithm are too communication intensive to be commonly applied in full and at high frequency in a distributed system.

☞ Therefore a distributed version needs to:

☞ **Split** the system into nodes of reasonable locality
(keeping most processes close to the resources they require).

☞ **Organize** the nodes in an adequate topology (e.g. a tree).

☞ **Check** for deadlock inside nodes
with blocked resource requests and detect/avoid **local deadlock** *immediately*.

☞ **Exchange** resource status information
between nodes occasionally and detect **global deadlocks** *eventually*.

Deadlocks

Deadlock recovery

A deadlock has been detected ☞ now what?

Breaking the circular dependencies can be done by:

☞ Either *pre-empt* an assigned **resource** which is part of the deadlock.

☞ or *stop* a **process** which is part of the deadlock.

Usually neither choice can be implemented 'gracefully' and deals only with the symptoms.

Deadlock recovery does not address the reason for the problem!

(i.e. the deadlock situation can re-occur again immediately)

Deadlocks

Deadlock strategies:

- Deadlock prevention
  System prevents deadlocks by its structure or by full verification

  ☞ **The best approach if applicable.**

- Deadlock avoidance
  System state is checked with every resource assignment.

  ☞ **More generally applicable, yet computationally very expensive.**

- Deadlock detection & recovery
  Detect deadlocks and break them in a 'coordinated' way.

  ☞ **Less computationally expensive (as lower frequent), yet usually 'messy'.**

- Ignorance & random kill
  Kill or restart unresponsive processes, power-cycle the computer, …

  ☞ **More of a panic reaction than a method.**

Atomic & idempotent operations

Atomic operations

Definitions of atomicity:

An operation is atomic if the processes performing it …

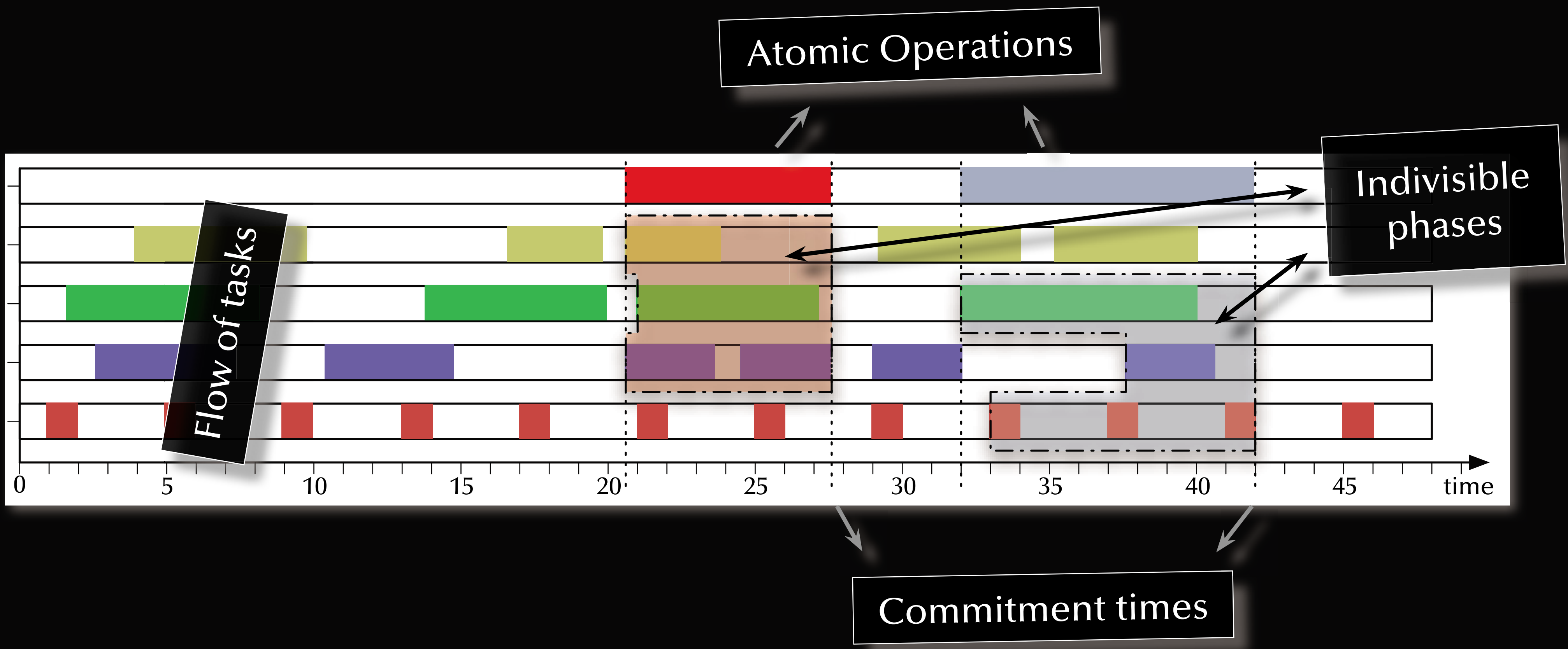
- **(by 'awareness')** … are not aware of the existence of any other active process, and no other active process is aware of the activity of the processes during the time the processes are performing the atomic operation.
- **(by communication)** … do not communicate with other processes while the atomic operation is performed.
- **(by means of states)** … cannot detect any outside state change and do not reveal their own state changes until the atomic operation is complete.

Short:

An atomic operation can be considered to be **indivisible** and **instantaneous.**

Atomic & idempotent operations

Atomic operations



Atomic & idempotent operations

Atomic operations

Important implications:

1. An atomic operation is either performed *in full* **or** *not at all*.
2. A failed atomic operation cannot have any impact on its surroundings (must keep or re-instantiate the full initial state).
3. If any part of an atomic operation fails, then the whole atomic operation is declared failed.
4. All parts of an atomic operations (including already completed parts) must be prepared to declare failure until the final global commitment.

Atomic & idempotent operations

Idempotent operations

Definition of idempotent operations:

An operation is idempotent if the observable effect of the operation are identical for the cases of executing the operation:

- once,
- multiple times,
- infinitely often.

Observations:

- Idempotent operations are often atomic, but do not need to be.
- Atomic operations do not need to be idempotent.
- Idempotent operations can ease the requirements for synchronization.

Reliability, failure & tolerance

'Terminology of failure' or 'Failing terminology'?

Reliability ::= measure of success with which a system conforms to its *specification*.

::= low failure rate.

Failure ::= a deviation of a system from its *specification*.

Error ::= the system state which leads to a failure.

Fault ::= the reason for an error.

Reliability, failure & tolerance

Faults during different phases of design

- Inconsistent or inadequate specifications

  ☞ frequent source for disastrous faults

- Software design errors

  ☞ frequent source for disastrous faults

- Component & communication system failures

  ☞ rare and mostly predictable

Reliability, failure & tolerance

Faults in the logic domain

- Non-termination / -completion

  Systems 'frozen' in a deadlock state, blocked for missing input, or in an infinite loop

  ☞ Watchdog timers required to handle the failure

- Range violations and other inconsistent states

  ☞ Run-time environment level exception handling required to handle the failure

- Value violations and other wrong results

  ☞ User-level exception handling required to handle the failure

Reliability, failure & tolerance

Faults in the time domain

- Transient faults

  ☞ Single 'glitches', interference, … very hard to handle

- Intermittent faults

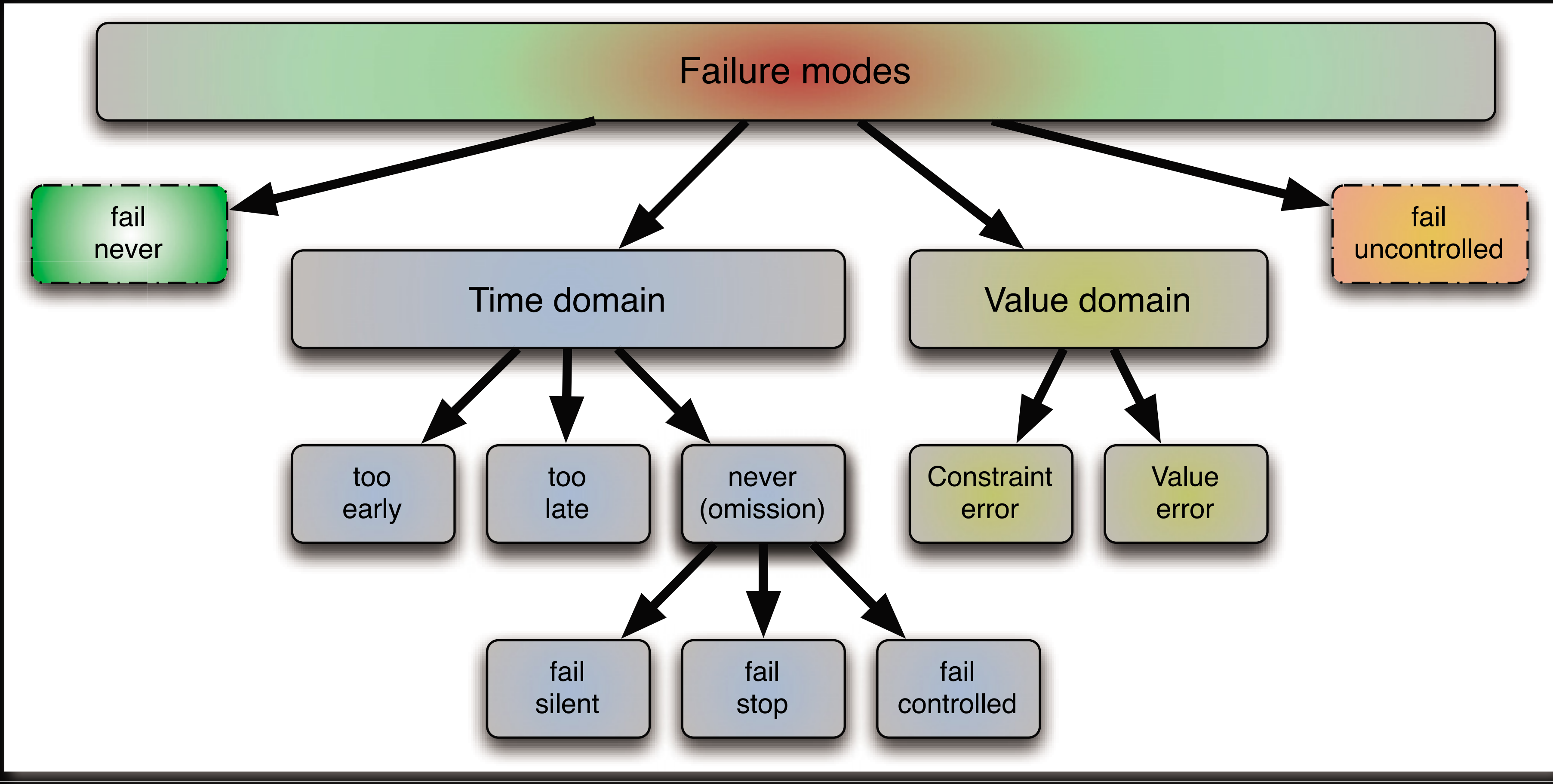
  ☞ Faults of a certain regularity … require careful analysis

- Permanent faults

  ☞ Faults which stay … the easiest to find

Reliability, failure & tolerance

Observable failure modes



Reliability, failure & tolerance

Fault prevention, avoidance, removal, …

and / or

☞ **Fault tolerance**

Reliability, failure & tolerance

Fault tolerance

- Full fault tolerance

  the system continues to operate in the presence of 'foreseeable' error conditions , **without any significant loss of functionality or performance** — even though this might reduce the achievable total operation time.

- Graceful degradation (fail soft)

  the system continues to operate in the presence of 'foreseeable' error conditions, **while accepting a partial loss of functionality or performance.**

- Fail safe

  the system halts and maintains its integrity.

☞ Full fault tolerance is not maintainable for an infinite operation time!

☞ Graceful degradation might have multiple levels of reduced functionality.

Summary

Safety & Liveness

- **Liveness**
  - Fairness
- **Safety**
  - Deadlock detection
  - Deadlock avoidance
  - Deadlock prevention
- **Atomic & Idempotent operations**
  - Definitions & implications
- **Failure modes**
  - Definitions, fault sources and basic fault tolerance