departamento de informática
FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

Monitoring Concurrency Errors: Detection of Deadlocks, Atomicity Violations, and Data Races (1)

Concurrency and Parallelism — 2017-18

Master in Computer Science

(Mestrado Integrado em Eng. Informática)

Joao Lourenço <joao.lourenco@fct.unl.pt>

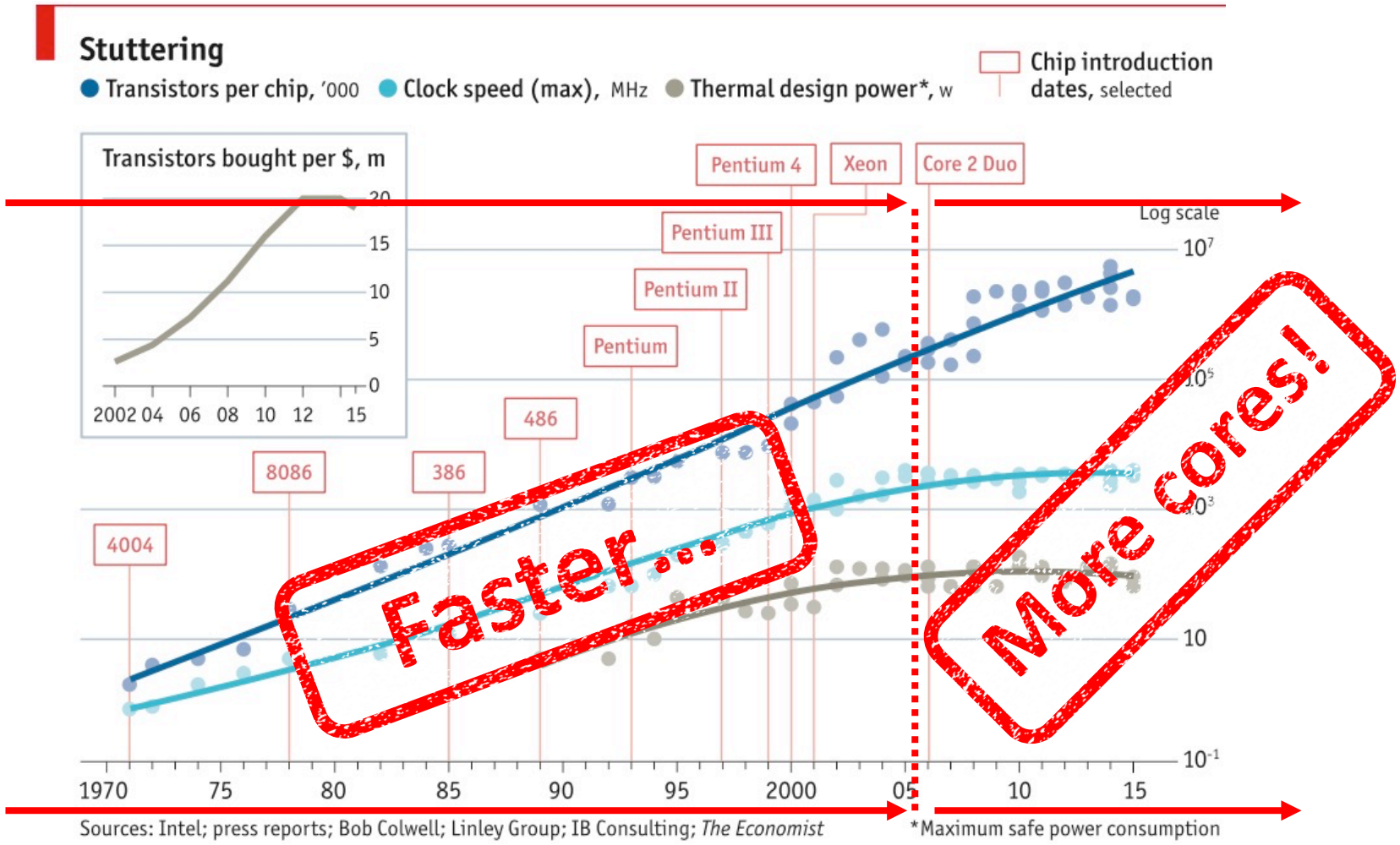
Agenda

- Why are we here?
- Concurrency Anomalies
- Assigning Semantics to Concurrent Programs
- Concurrency Errors
  - Detection of data races
  - Detection of high-level data races and stale value errors
  - Detection of deadlocks

Why are we here?

It is Moore's fault! ;)

Moore's Law


Stuttering
Transistors per chip, '000
Clock speed (max), MHz
Thermal design power*, w
Chip introduction dates, selected
Transistors bought per $, m
Pentium 4
Xeon
Core 2 Duo
Pentium III
Pentium II
Pentium
486
8086
386
4004
Log scale
Faster...
More cores!
1970
75
80
85
90
95
2000
05
10
15
Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; The Economist
*Maximum safe power consumption

Is there a problem?

To use all the processor cores…

…we need multiple cooperating processes!

But… Is there a problem?

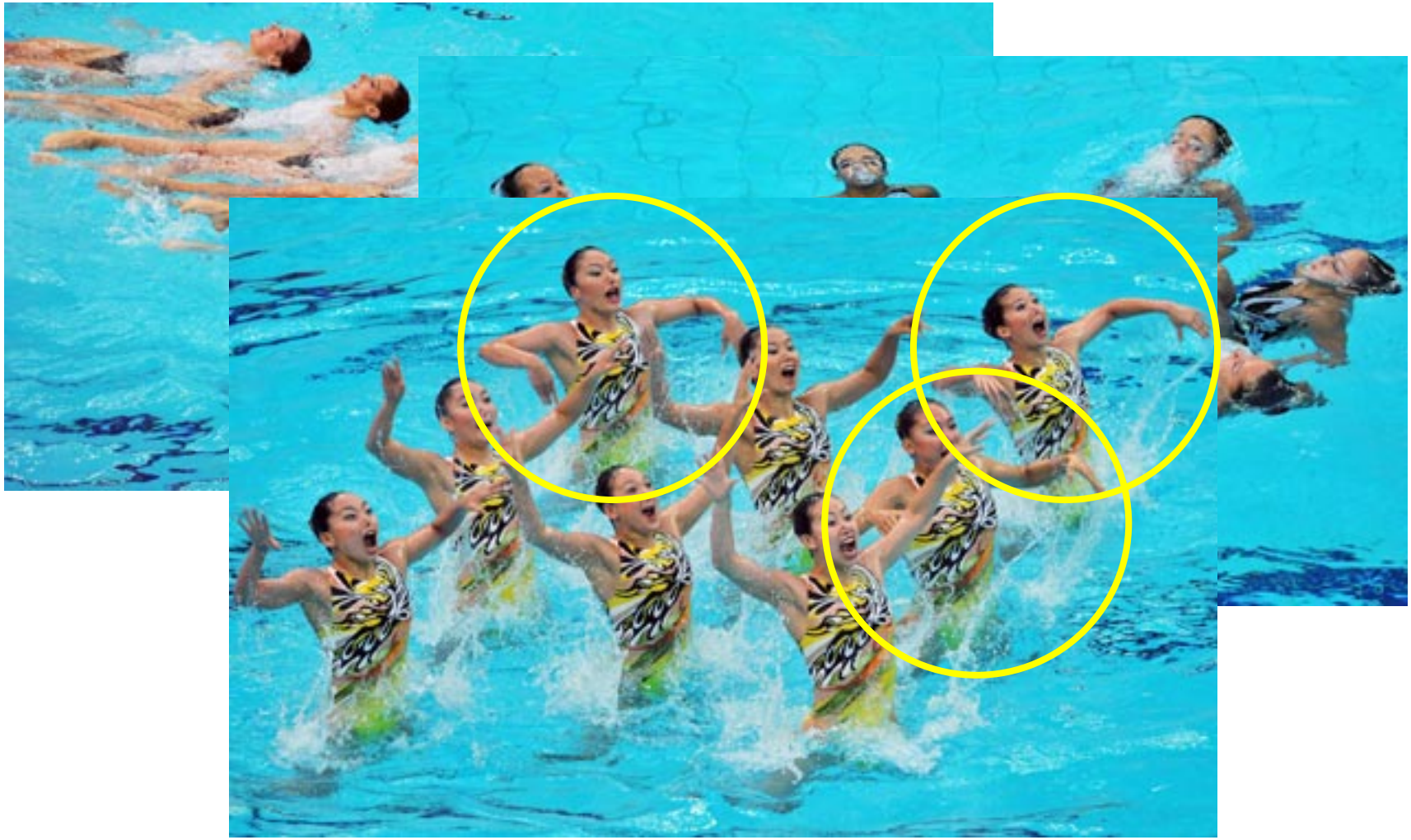
But… Is there a problem?

Concurrency Anomalies

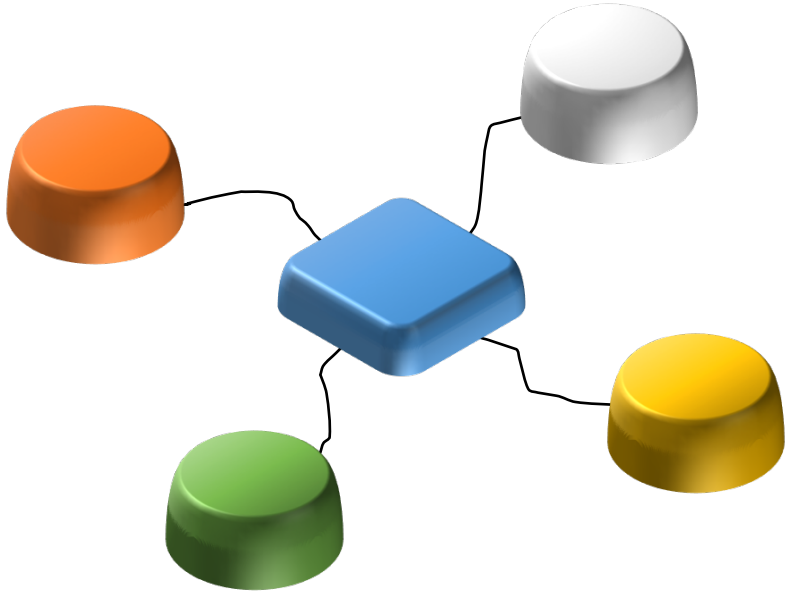
What and why?

Single Process

Multiple Processes



Sharing Resources (unsync.)



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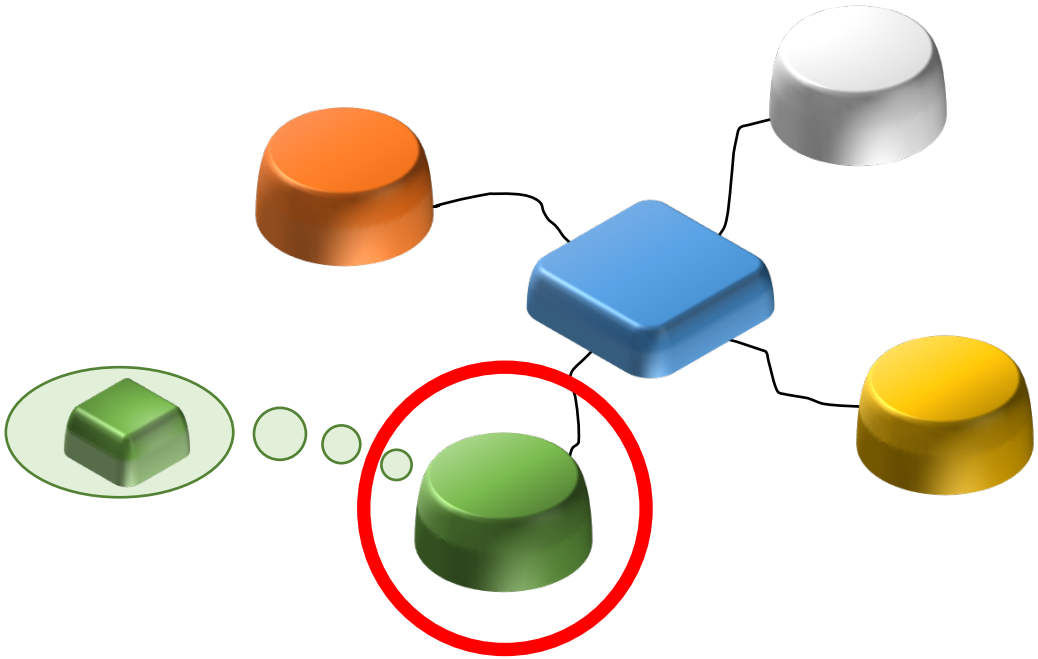

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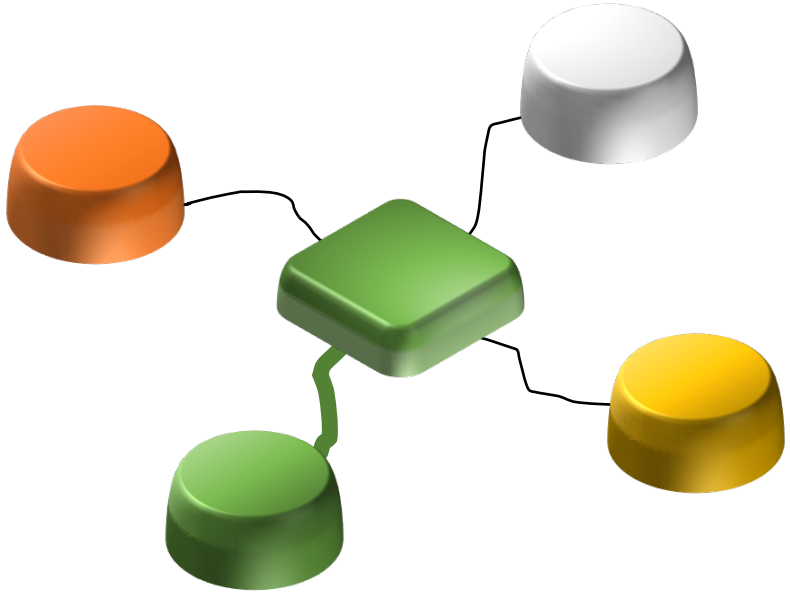

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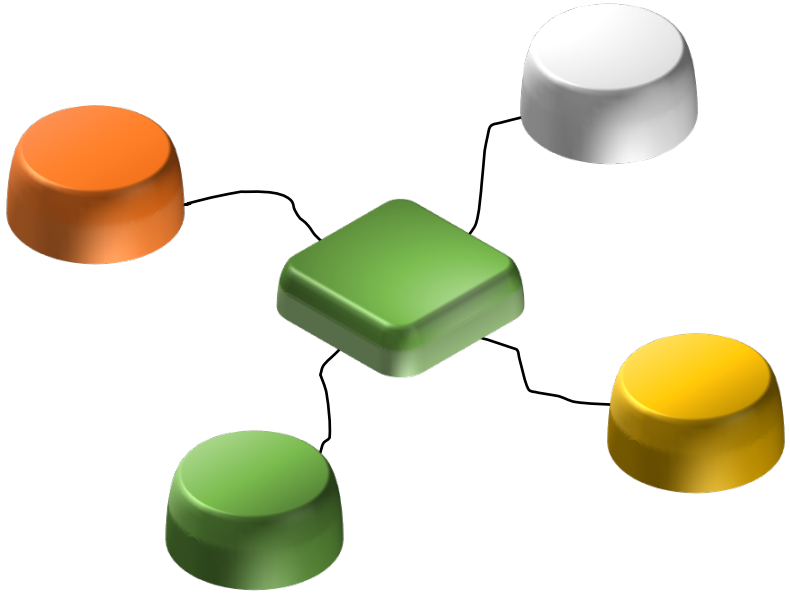

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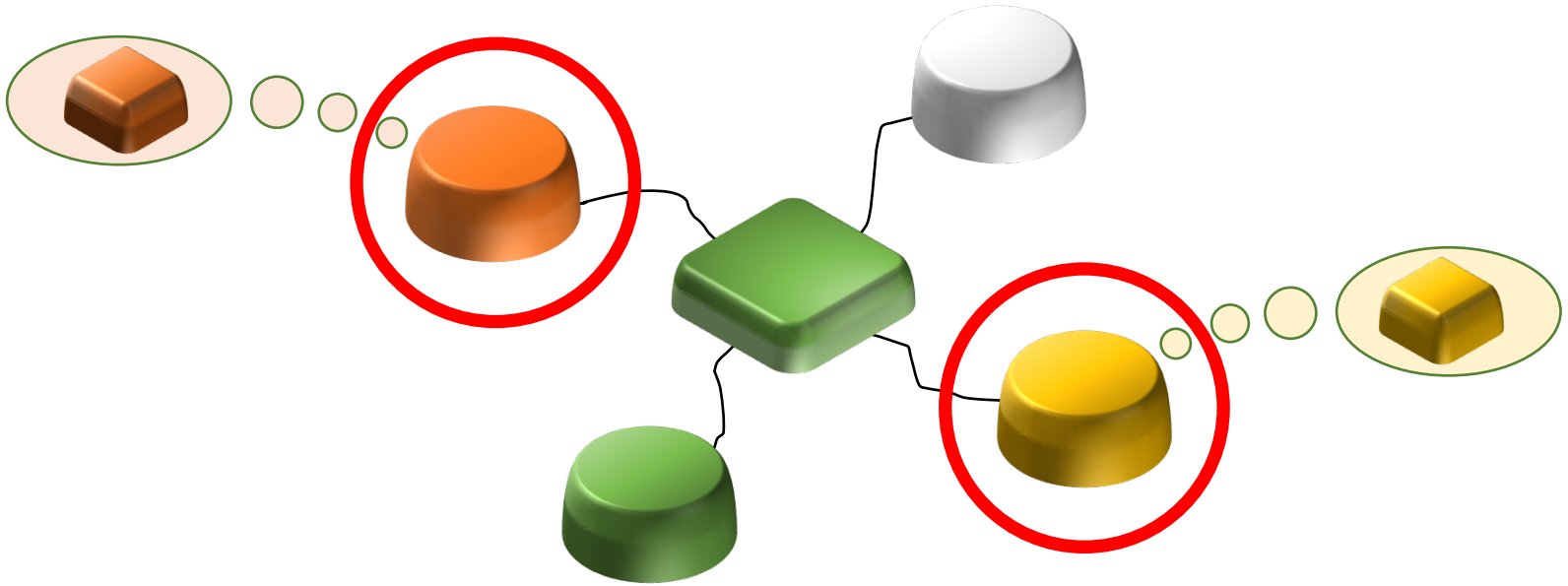

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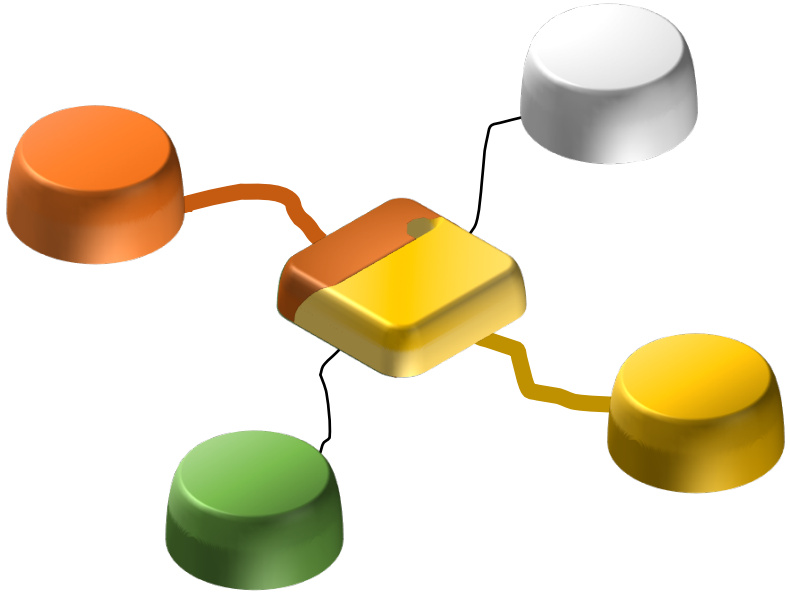

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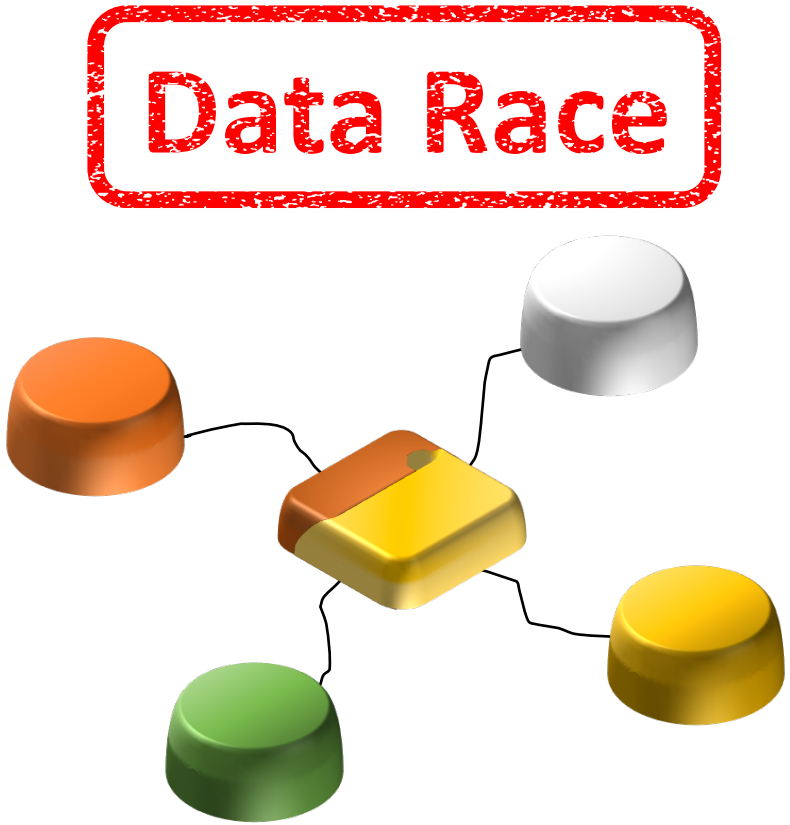
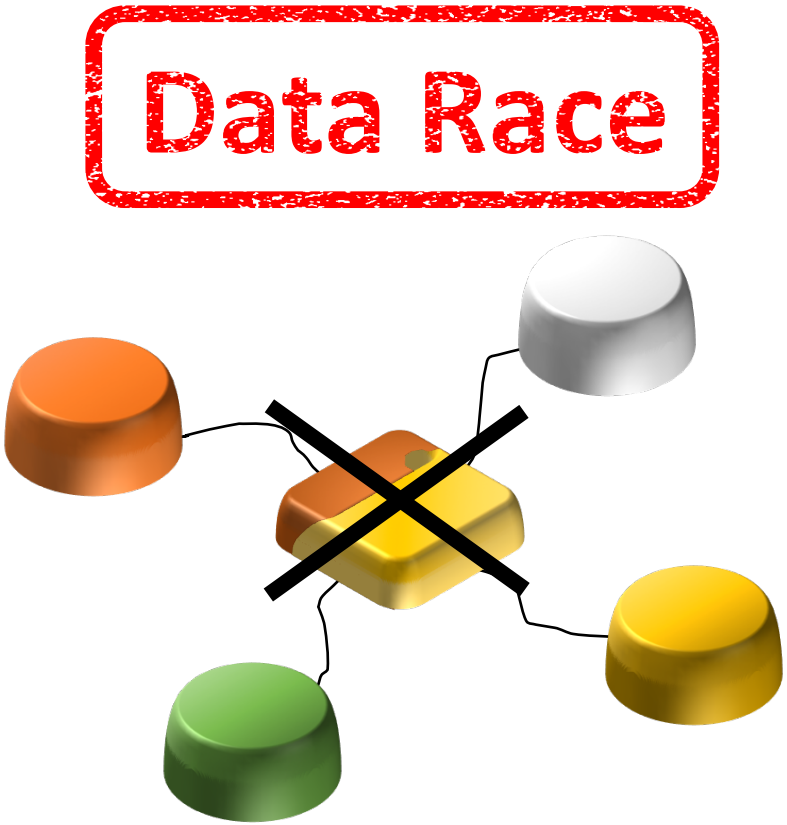


How to avoid Data Races?



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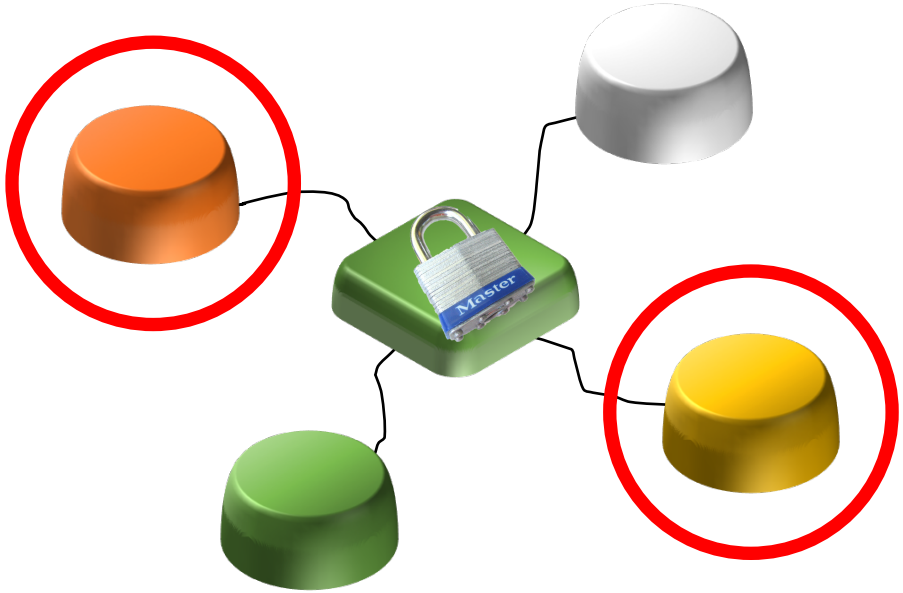

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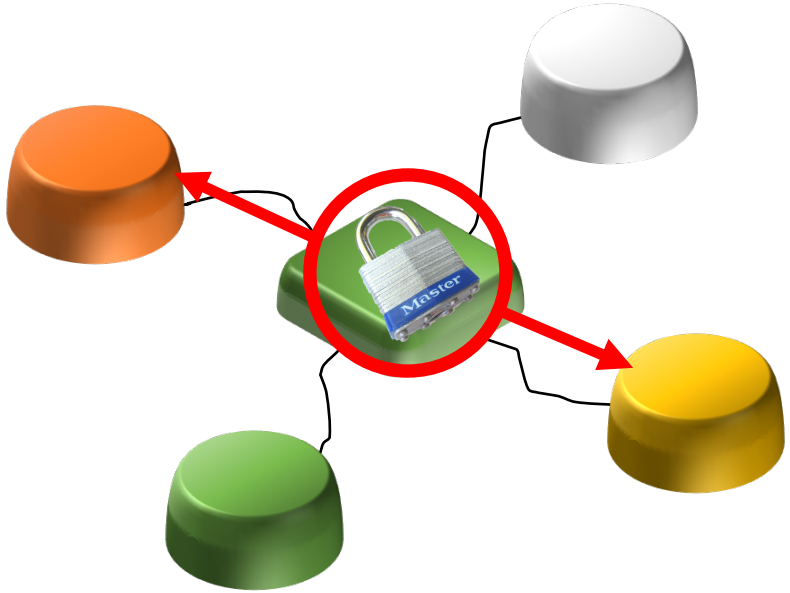

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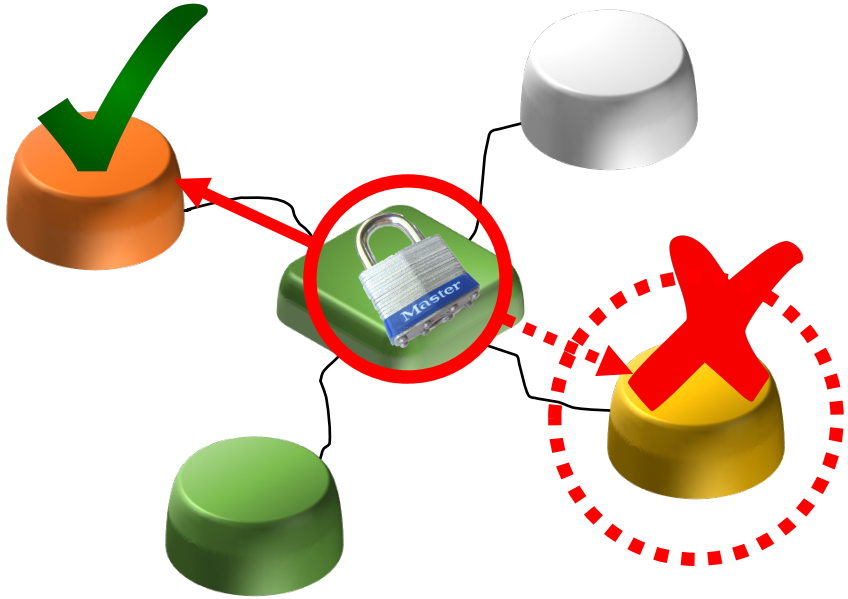

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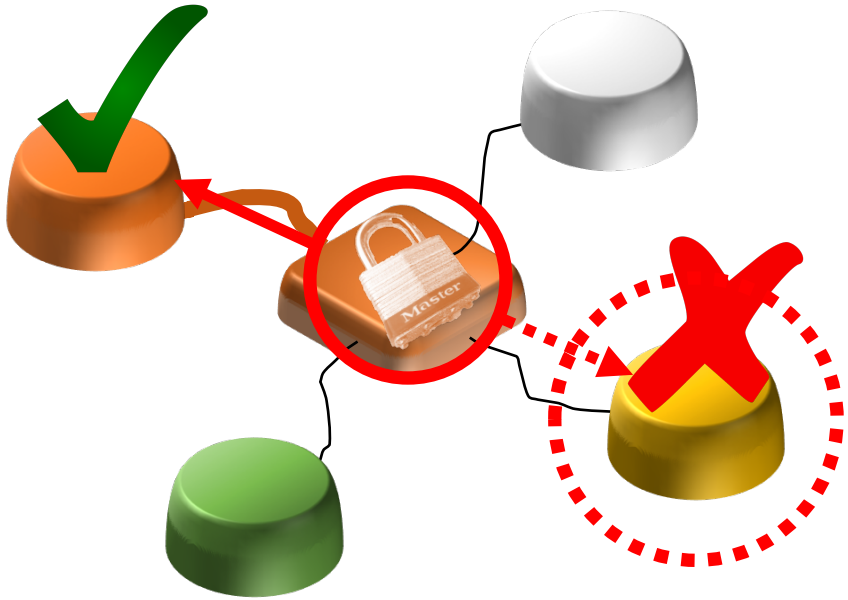

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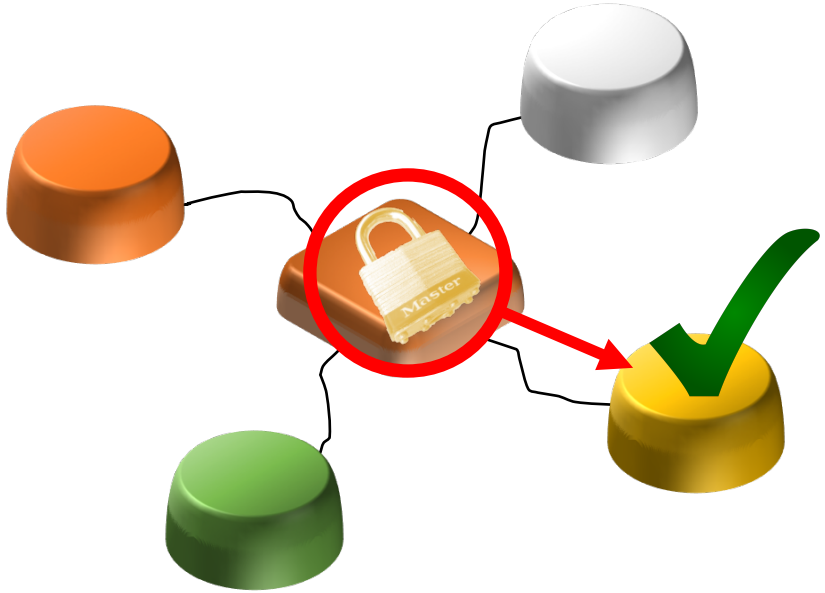

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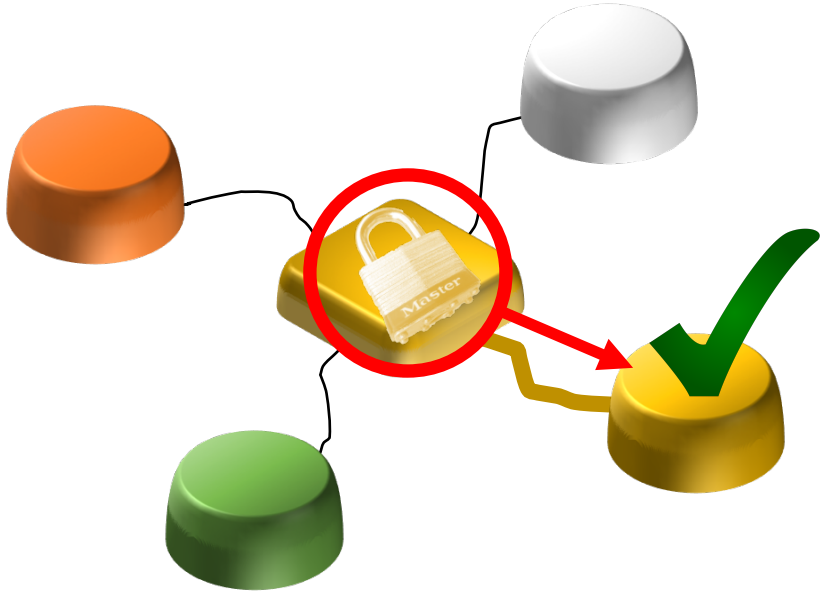

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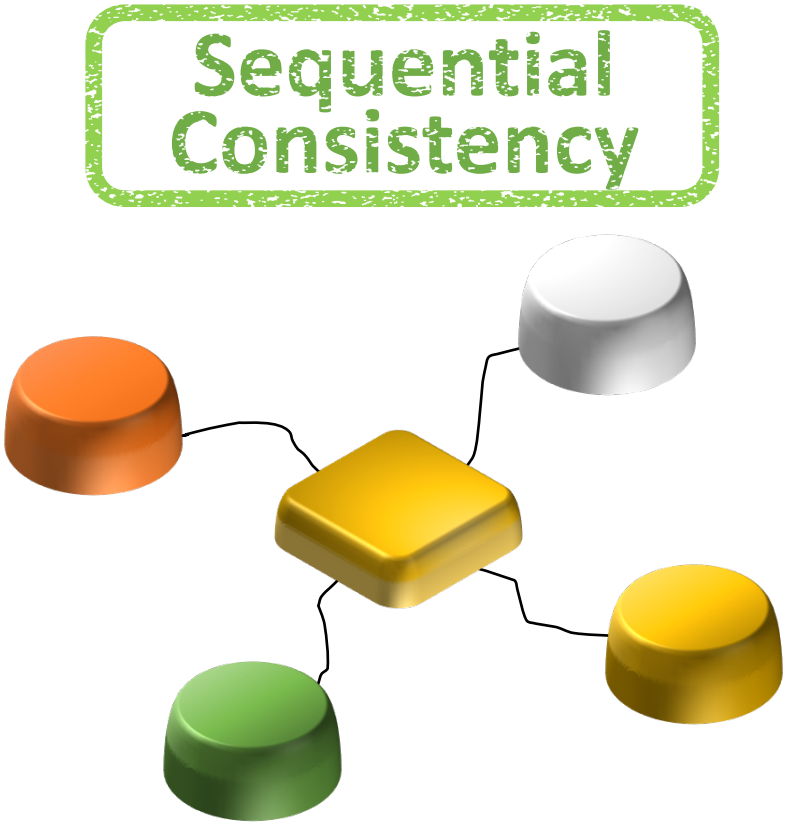
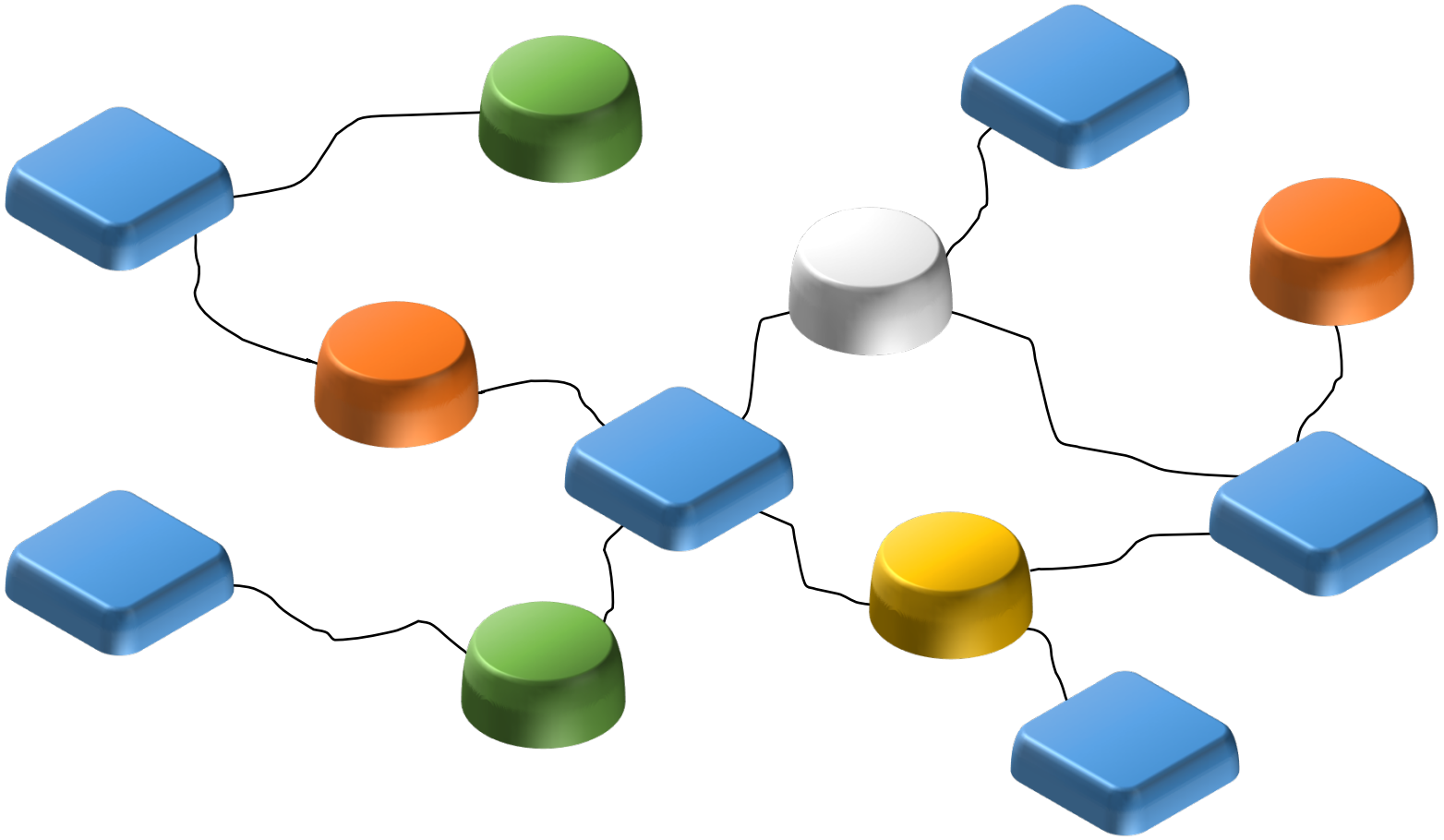
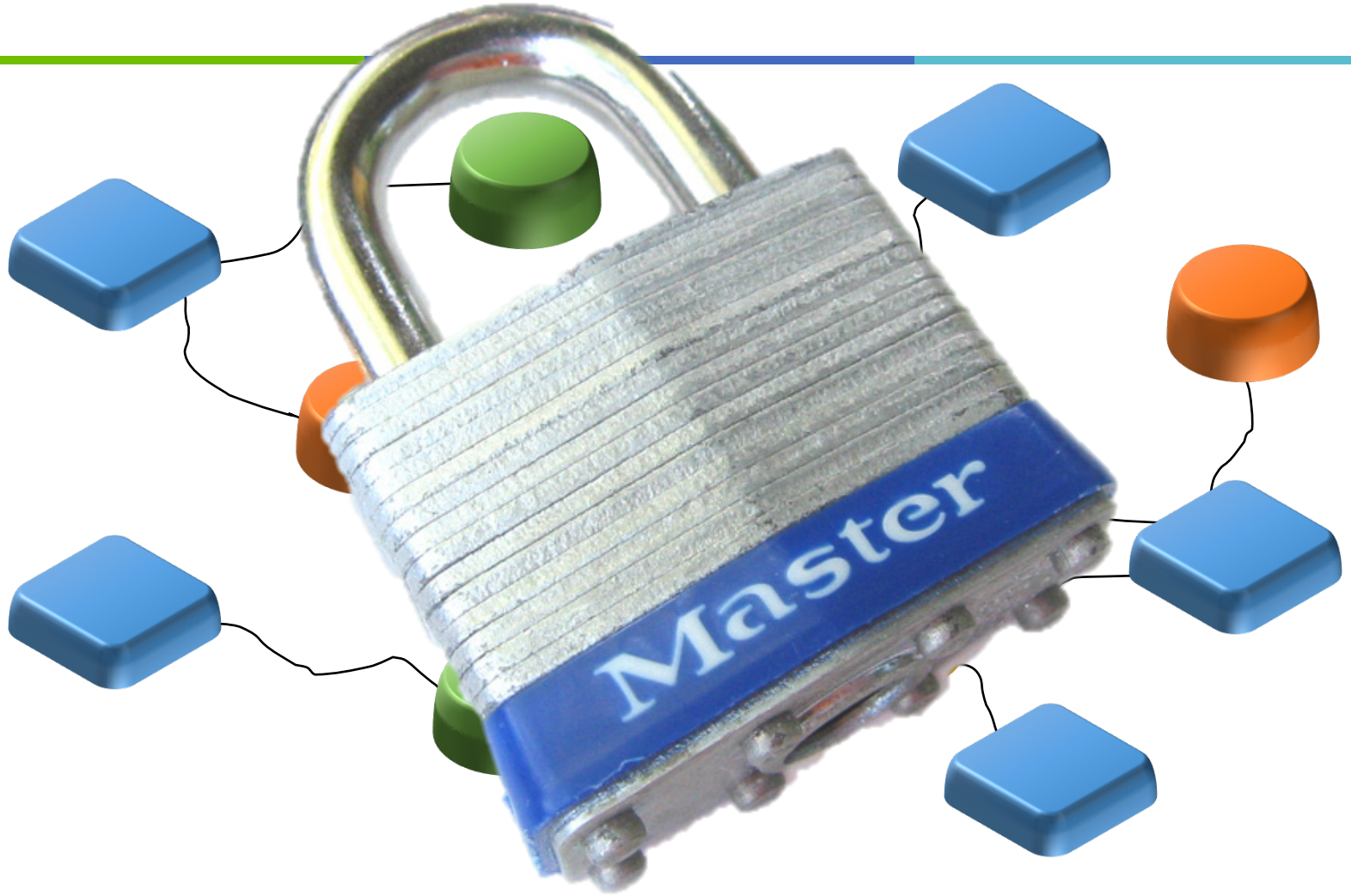


Sharing Multiple Resources



Sharing Multiple Resources



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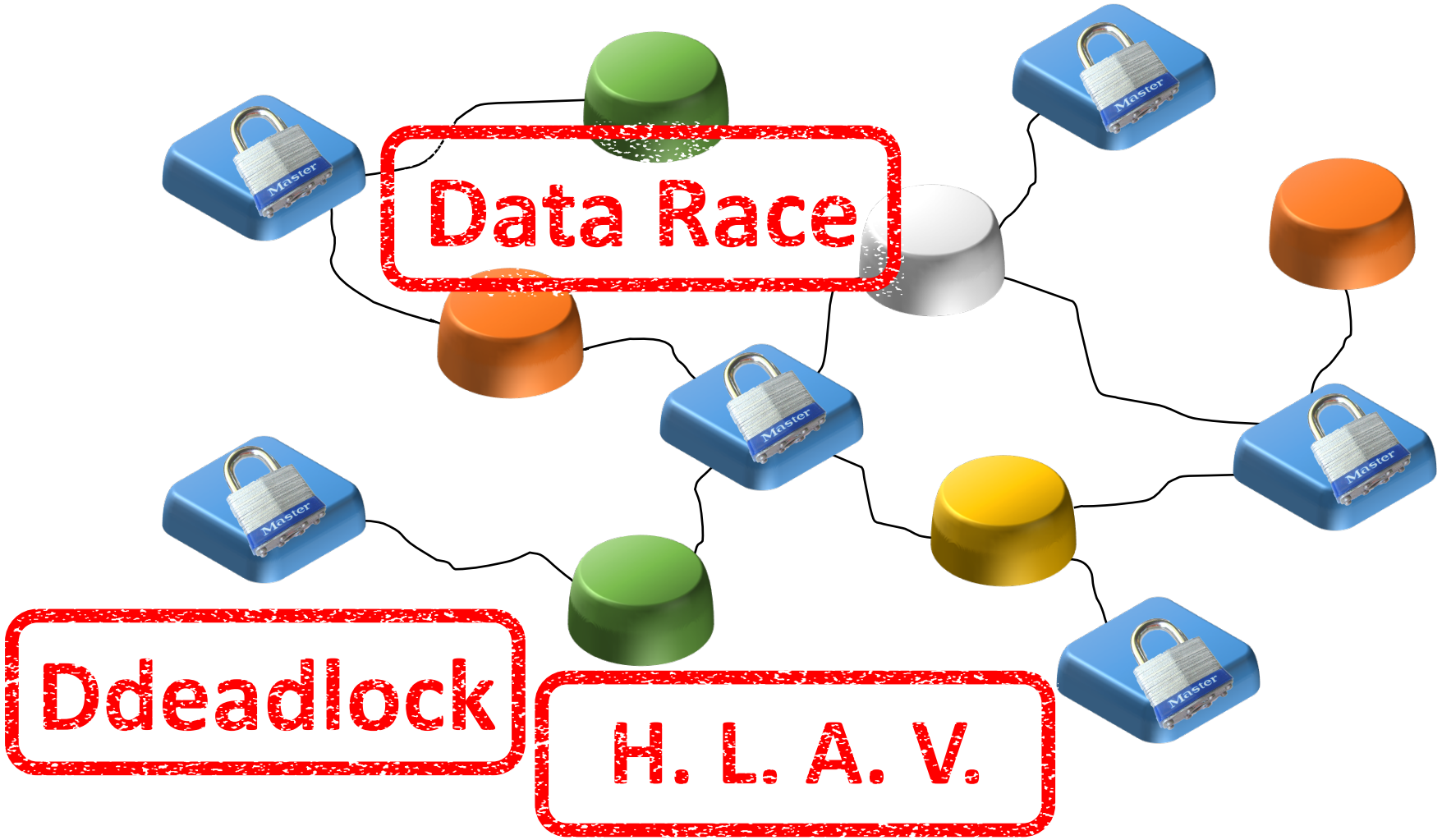

Assigning Semantics to Concurrent Programs

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X = Y = 0

X,Y => Global Vars
a, b => Local Vars

X = 1 Y = 2	a = Y b = X

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- What are the final values for 'X', 'Y', 'a' and 'b'?
  - X = 1, Y = 2

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- What are the final values for 'X', 'Y', 'a' and 'b'?
  - X = 1, Y = 2, a = ?, b = ?
- Depends on the interleavings of the assignments
  - Sequential Consistency [Lamport'79]
  - Program behavior = set of interleavings

Assigning Semantics to Concurrent Programs

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X = 1
Y = 2

a = Y
b = X

X = 1

Y = 2

a = Y

b = X

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Y = 2

a = Y
b = X

X = 1

Y = 2

a = Y

b = X

a=2, b=1

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X = 1 Y = 2	a = Y b = X

X = 1	X = 1
Y = 2	a = Y
a = Y	b = X
b = X	Y = 2

a=2, b=1

Assigning Semantics to Concurrent Programs

X = Y = 0

X,Y => Global Vars
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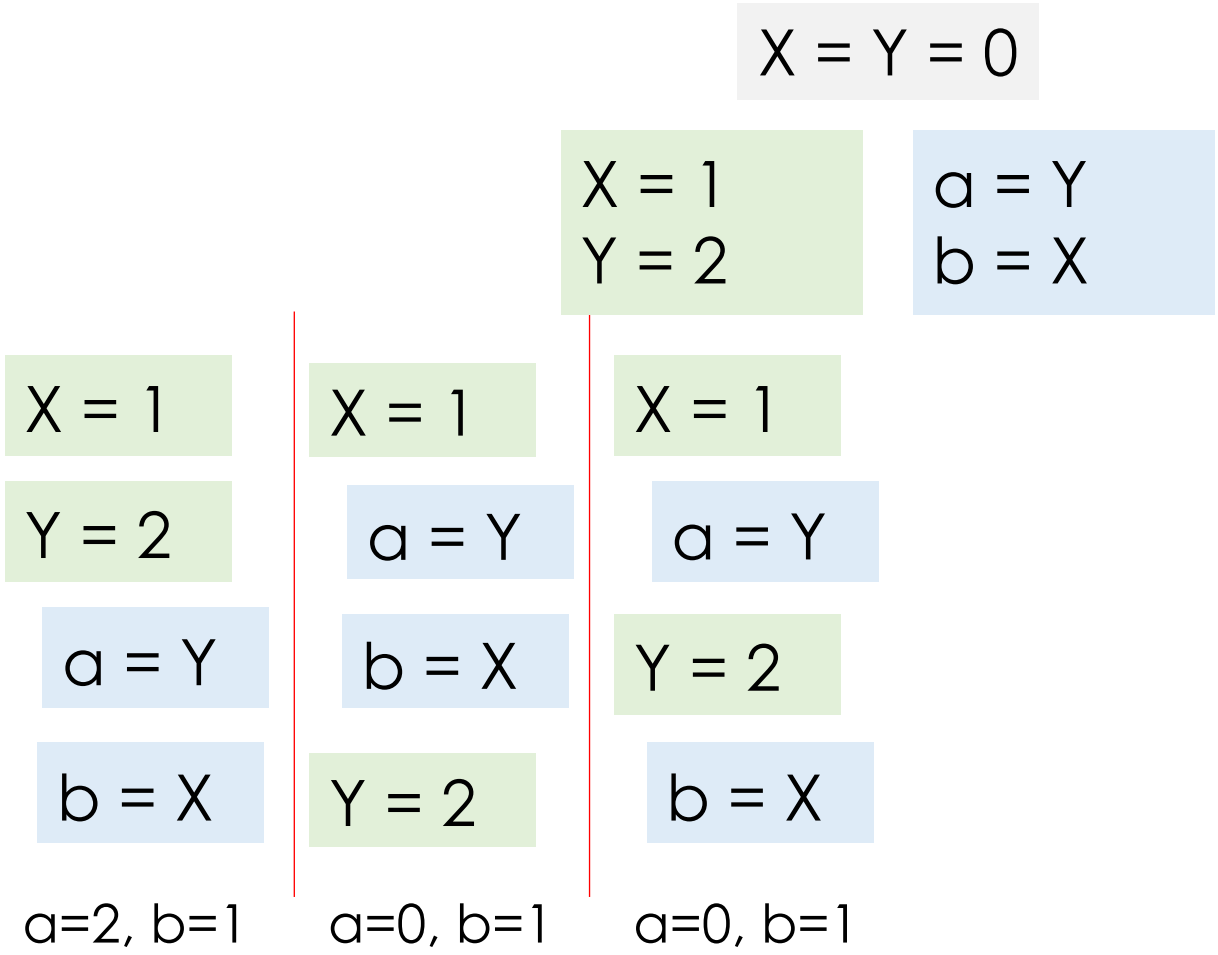
X = 1 Y = 2	a = Y b = X

X = 1	X = 1
Y = 2	a = Y
a = Y	b = X
b = X	Y = 2
a=2, b=1	a=0, b=1

Assigning Semantics to Concurrent Programs



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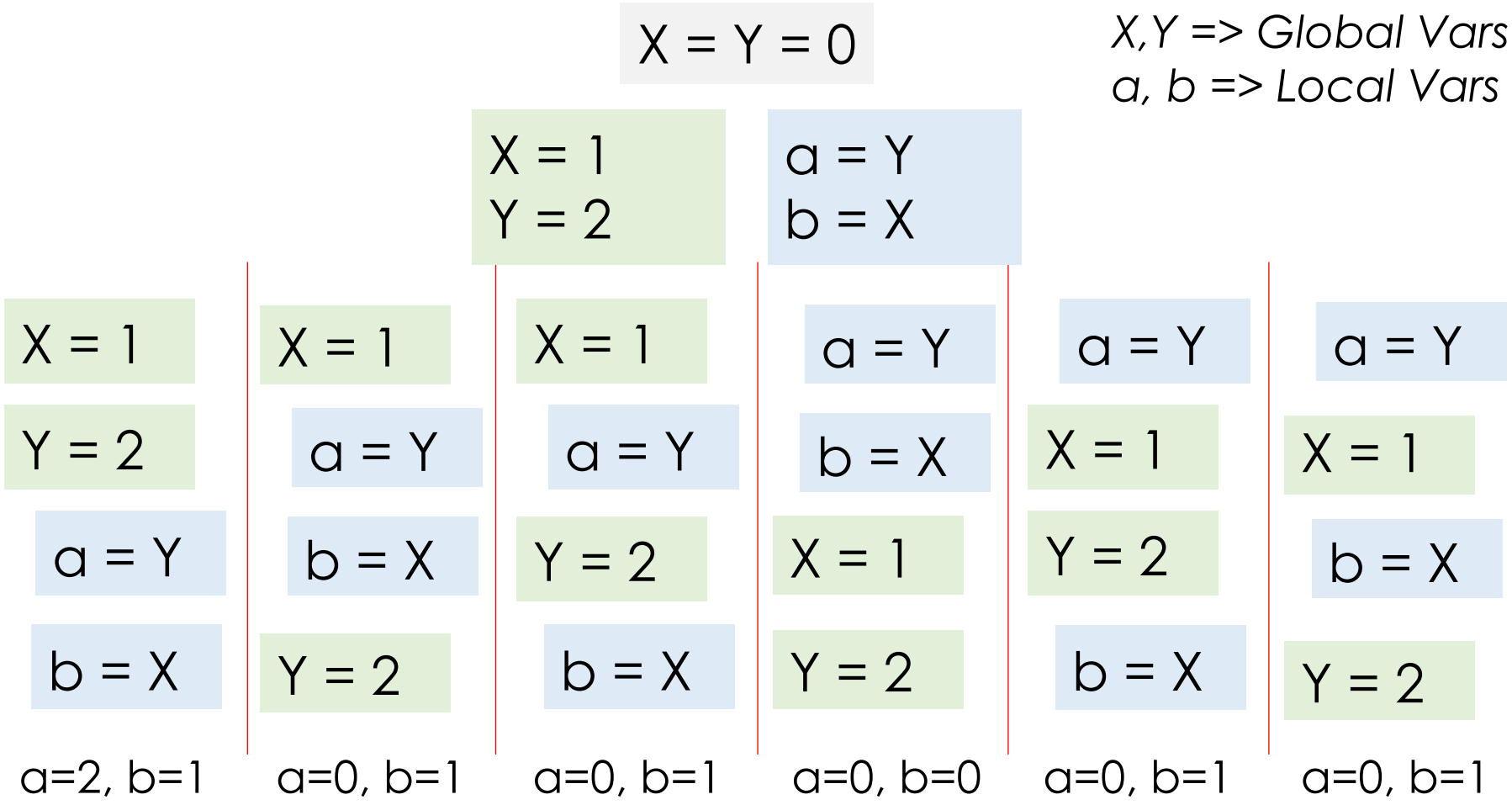
Assigning Semantics to Concurrent Programs

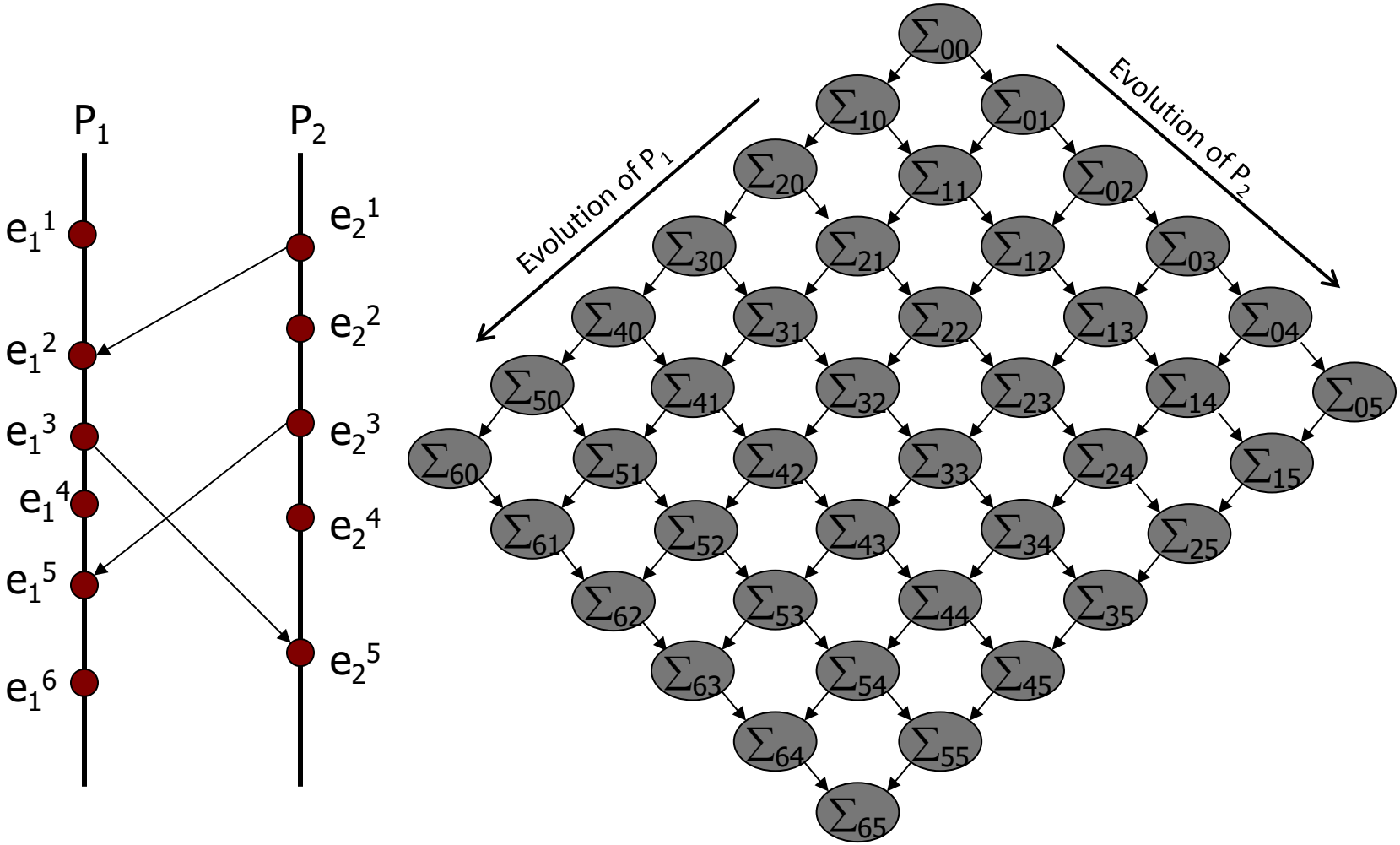


Sequential Consistency

- Instructions are executed by the order they appear in the program
- Memory behaves as a shared array
  - Reads and writes are effective immediately

- This is naturally true for sequential programs…

State explosion in concurrent programs



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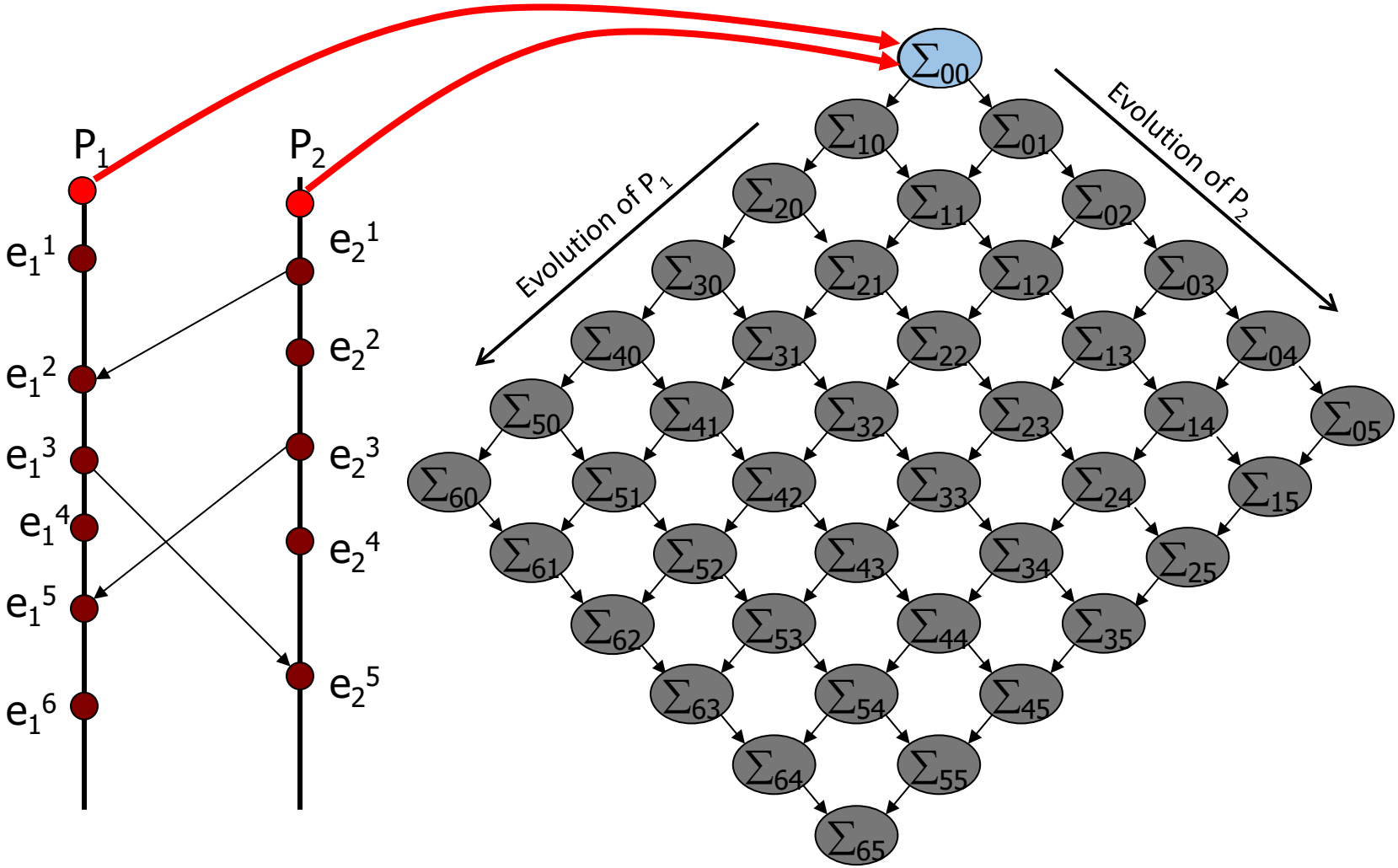

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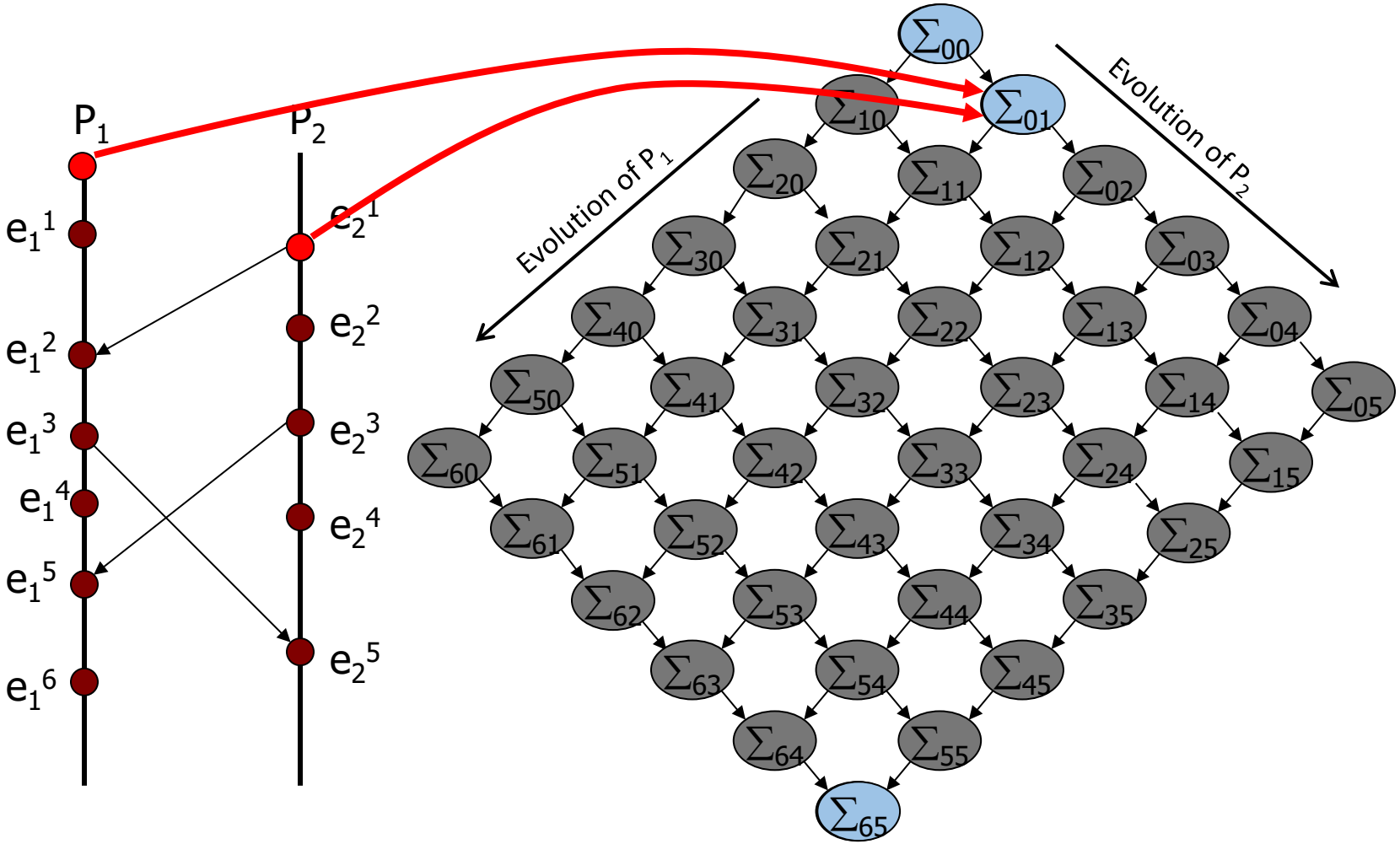

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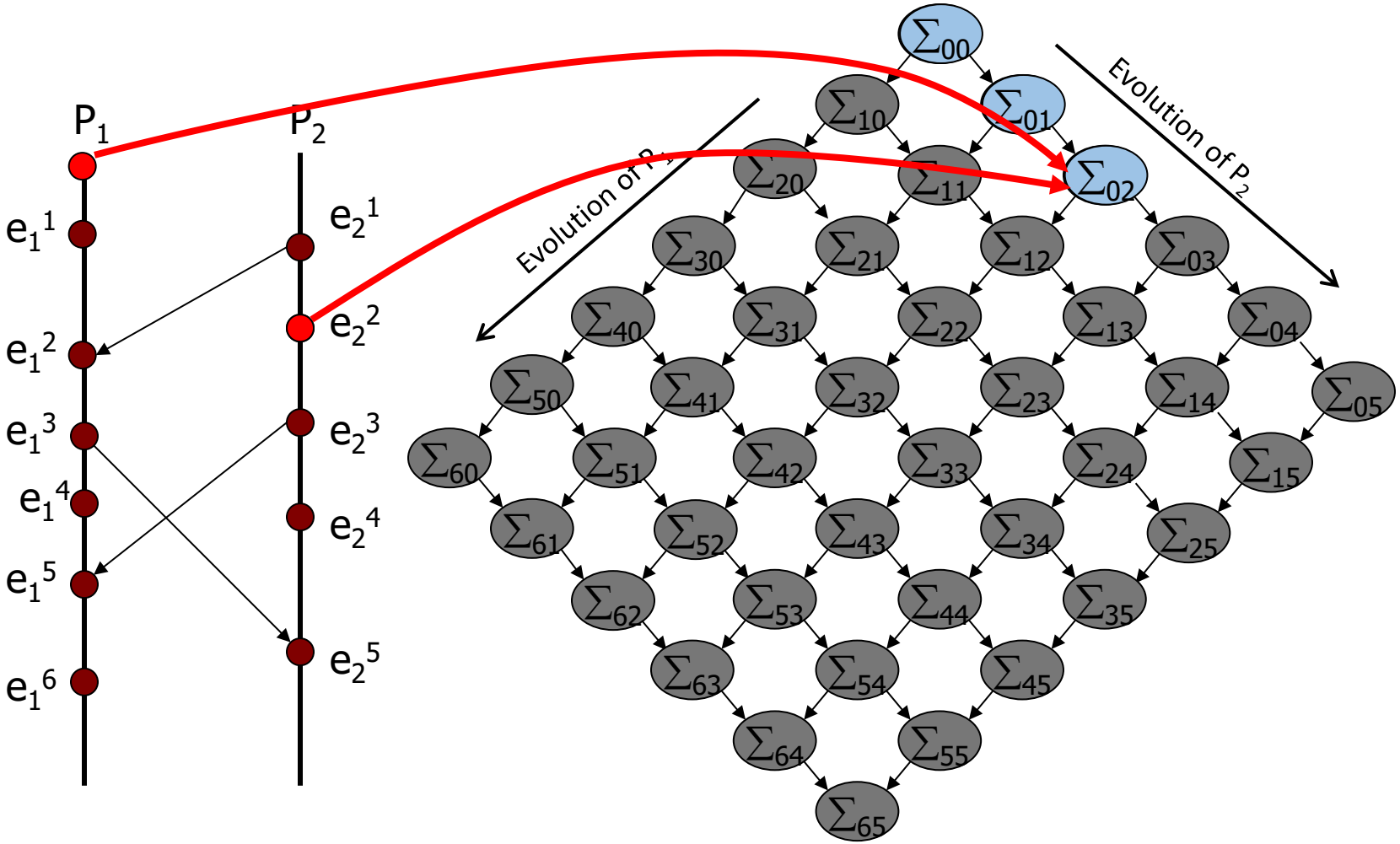

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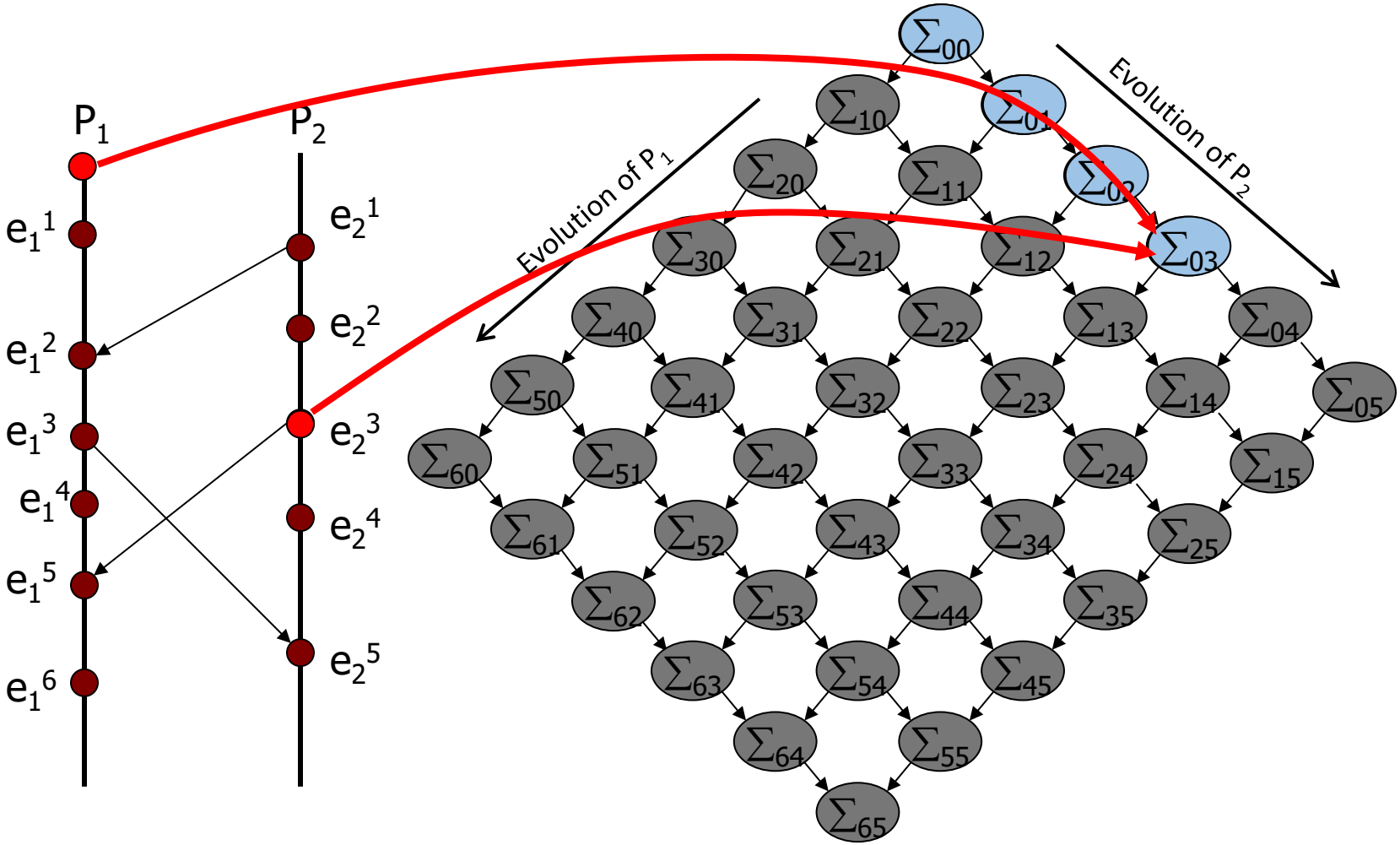

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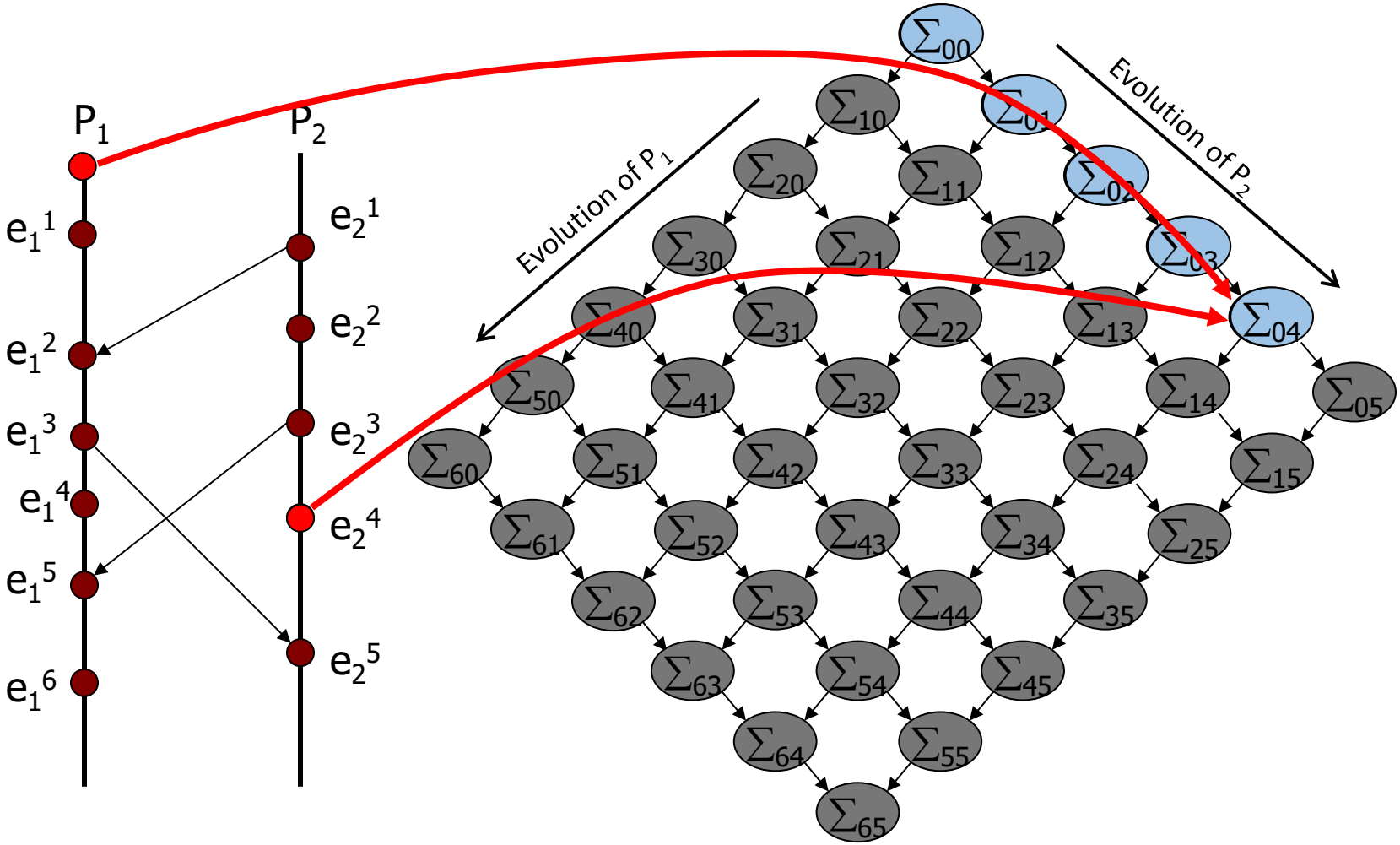

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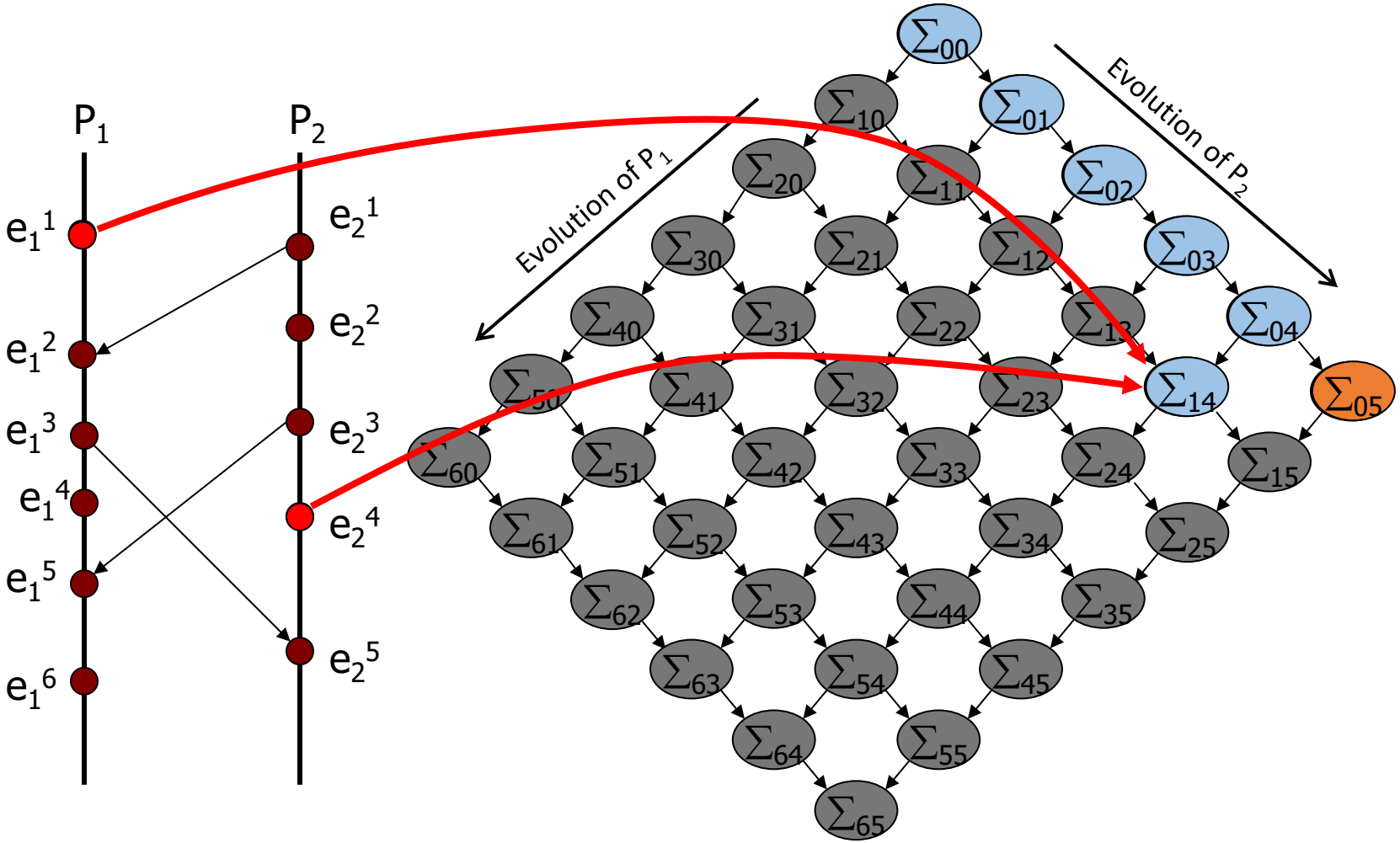

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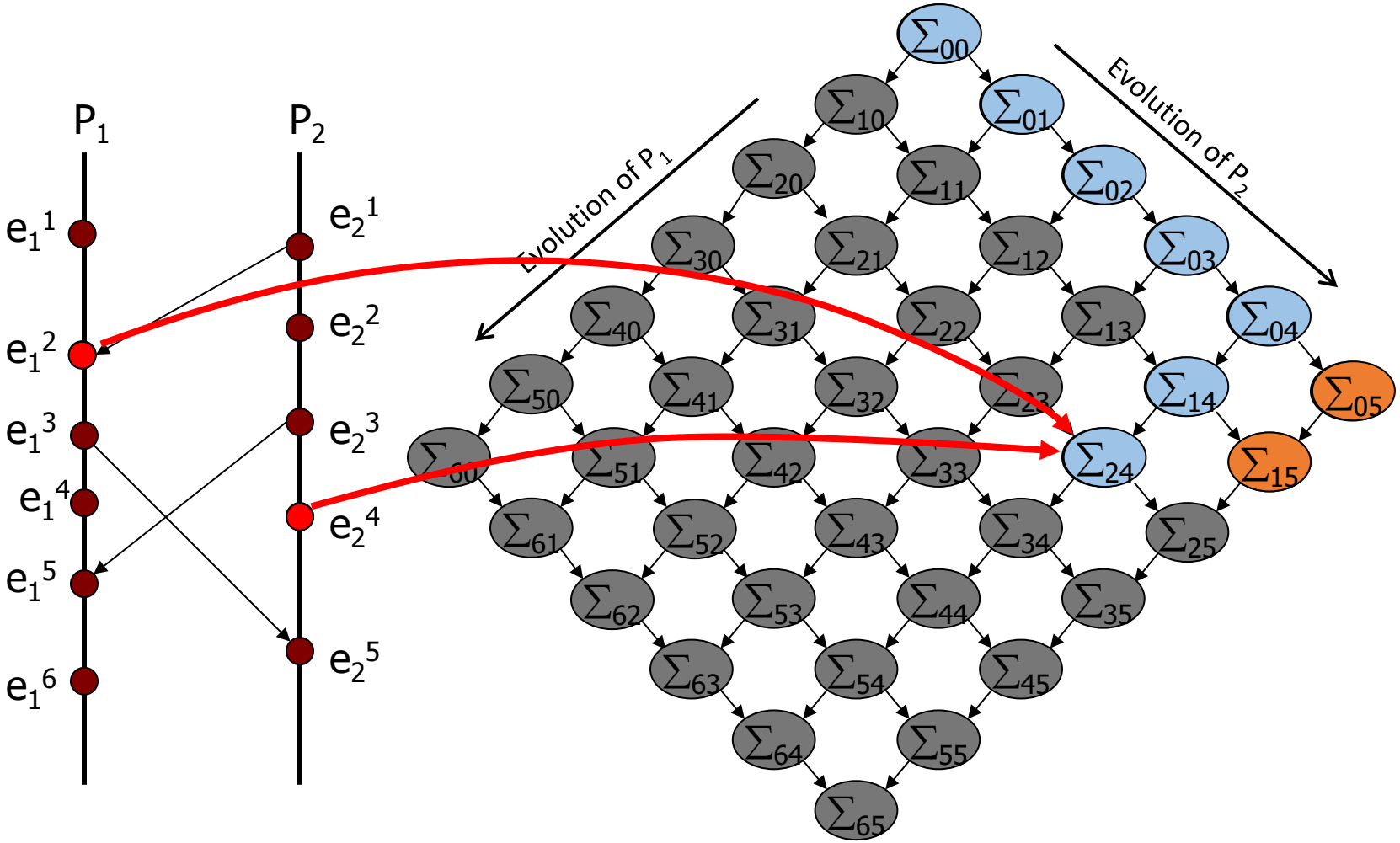

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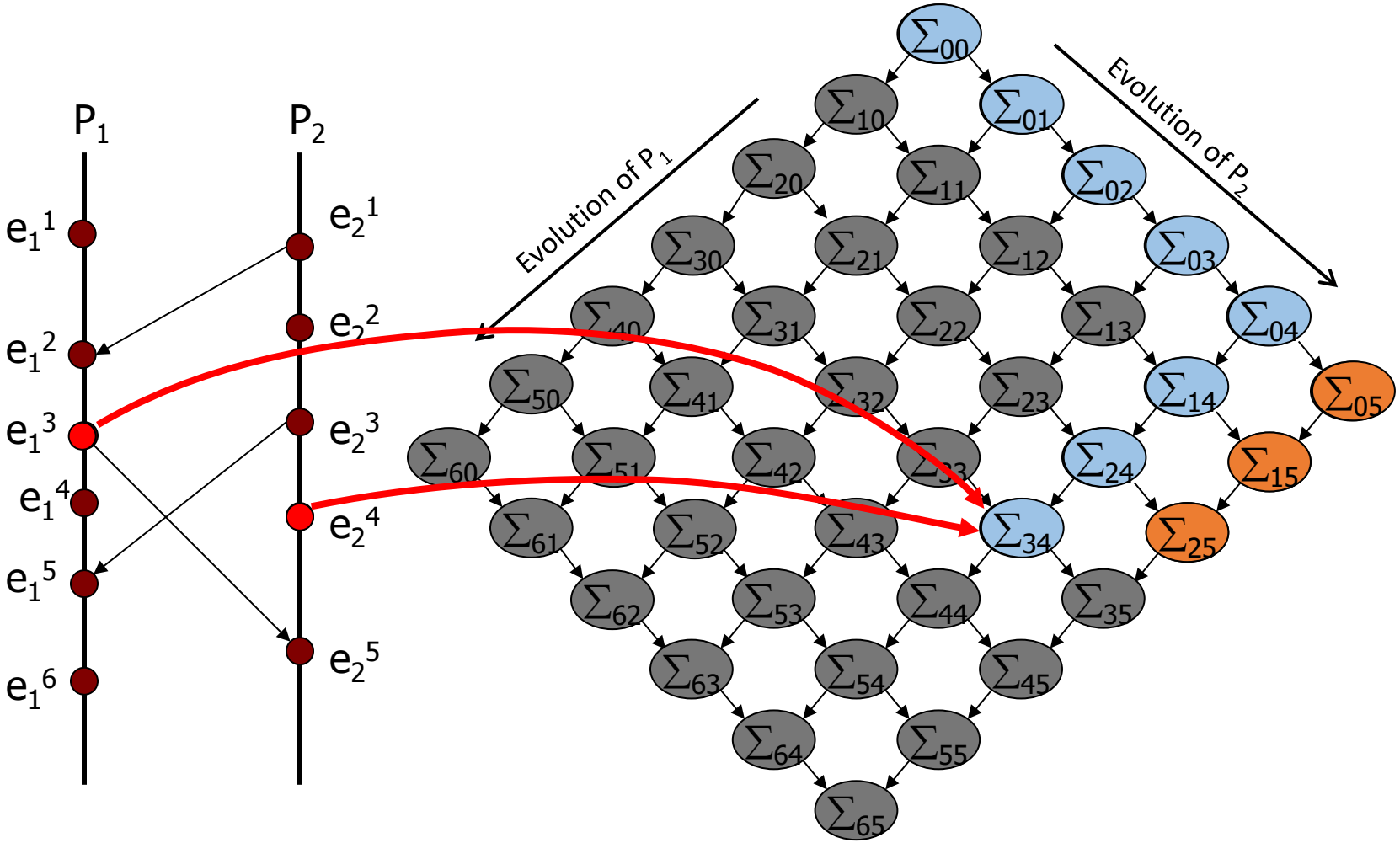

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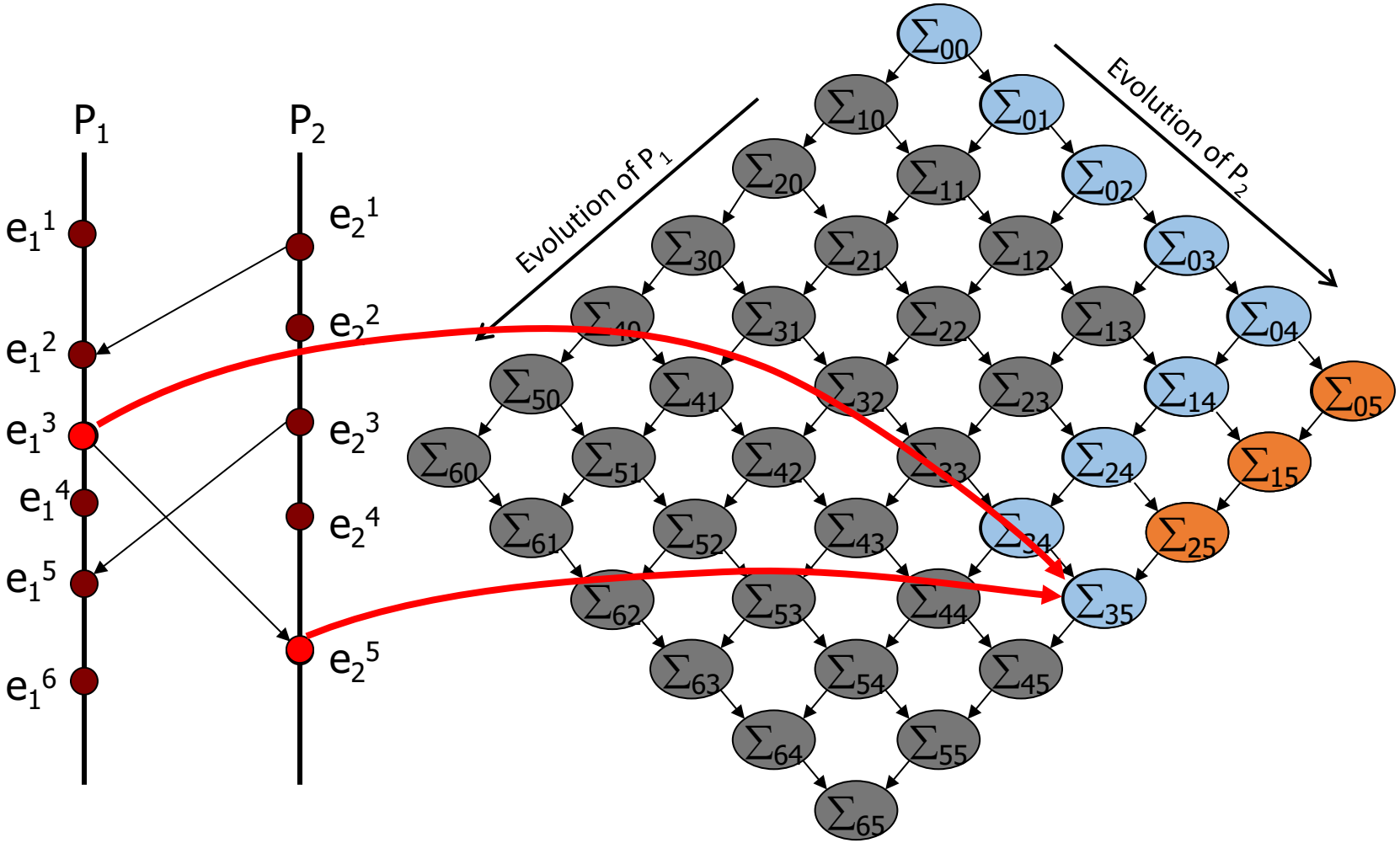

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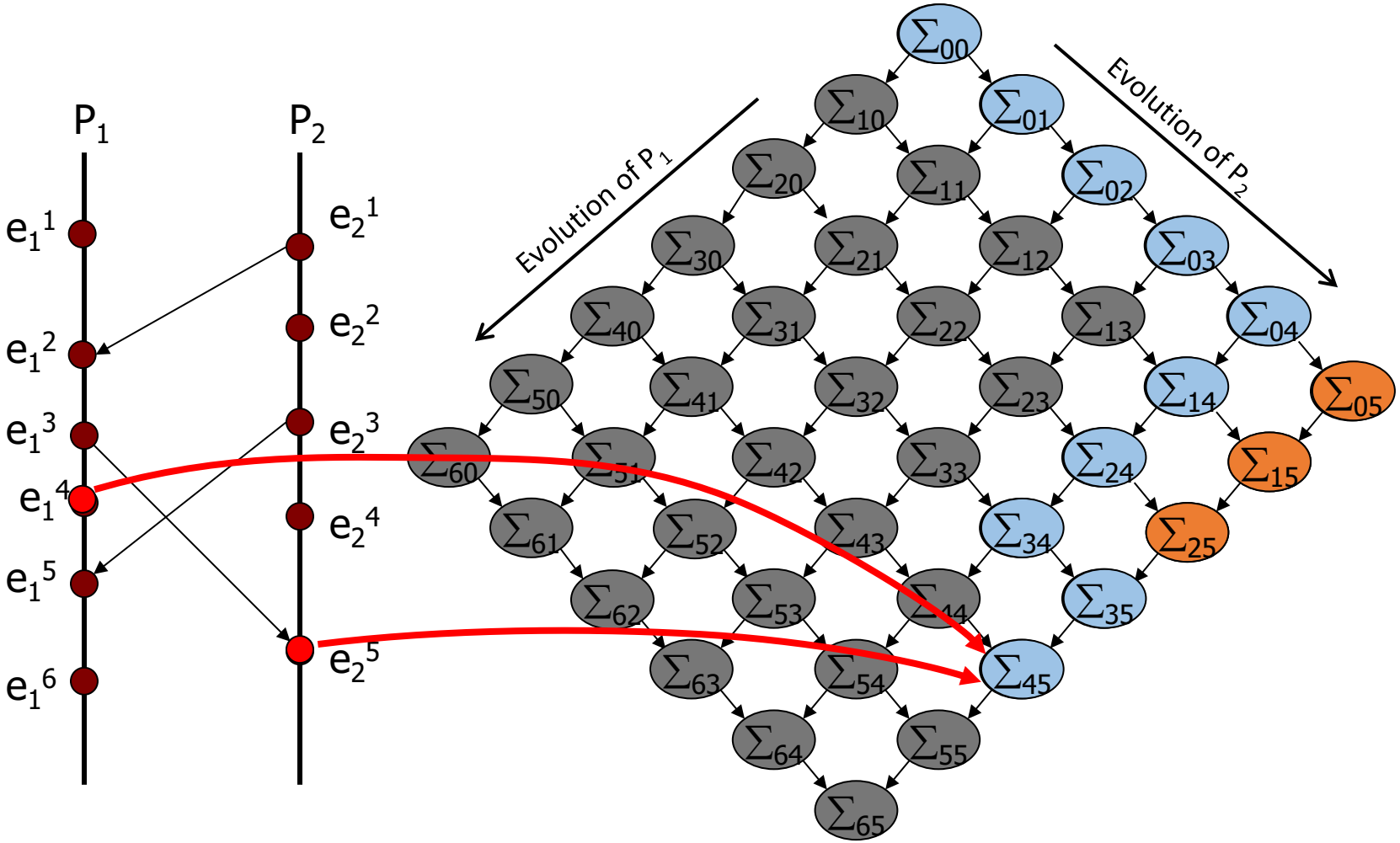

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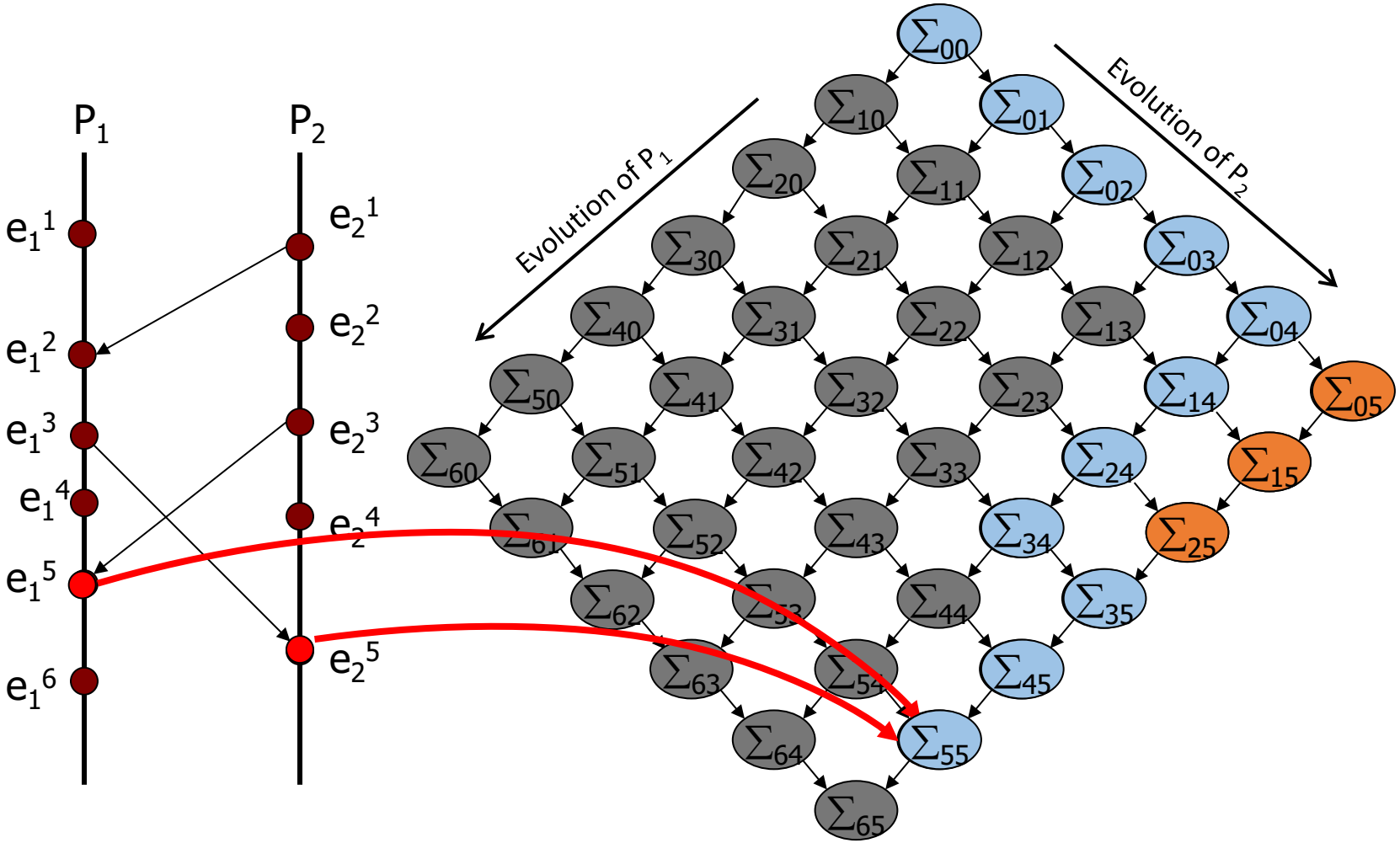

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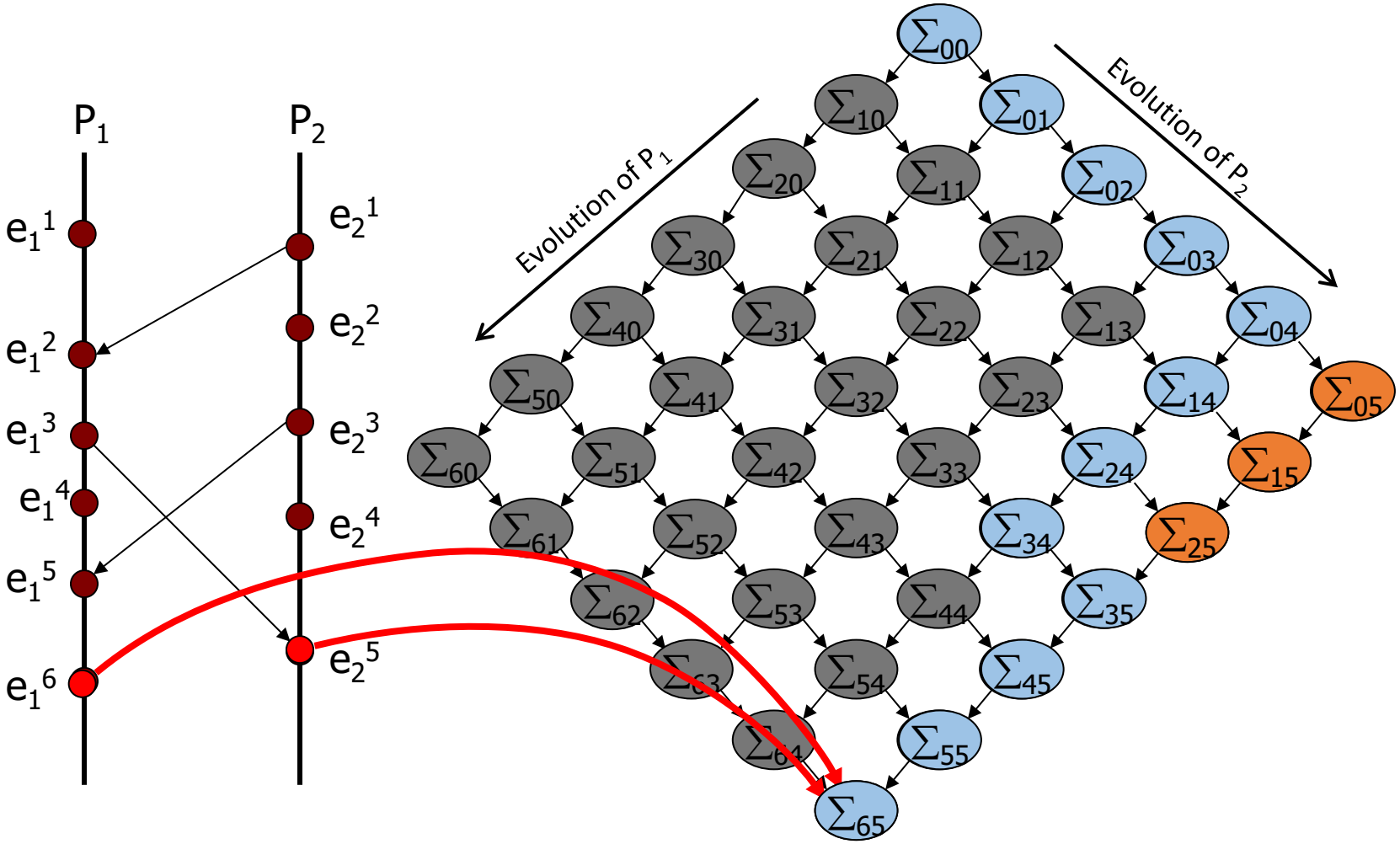

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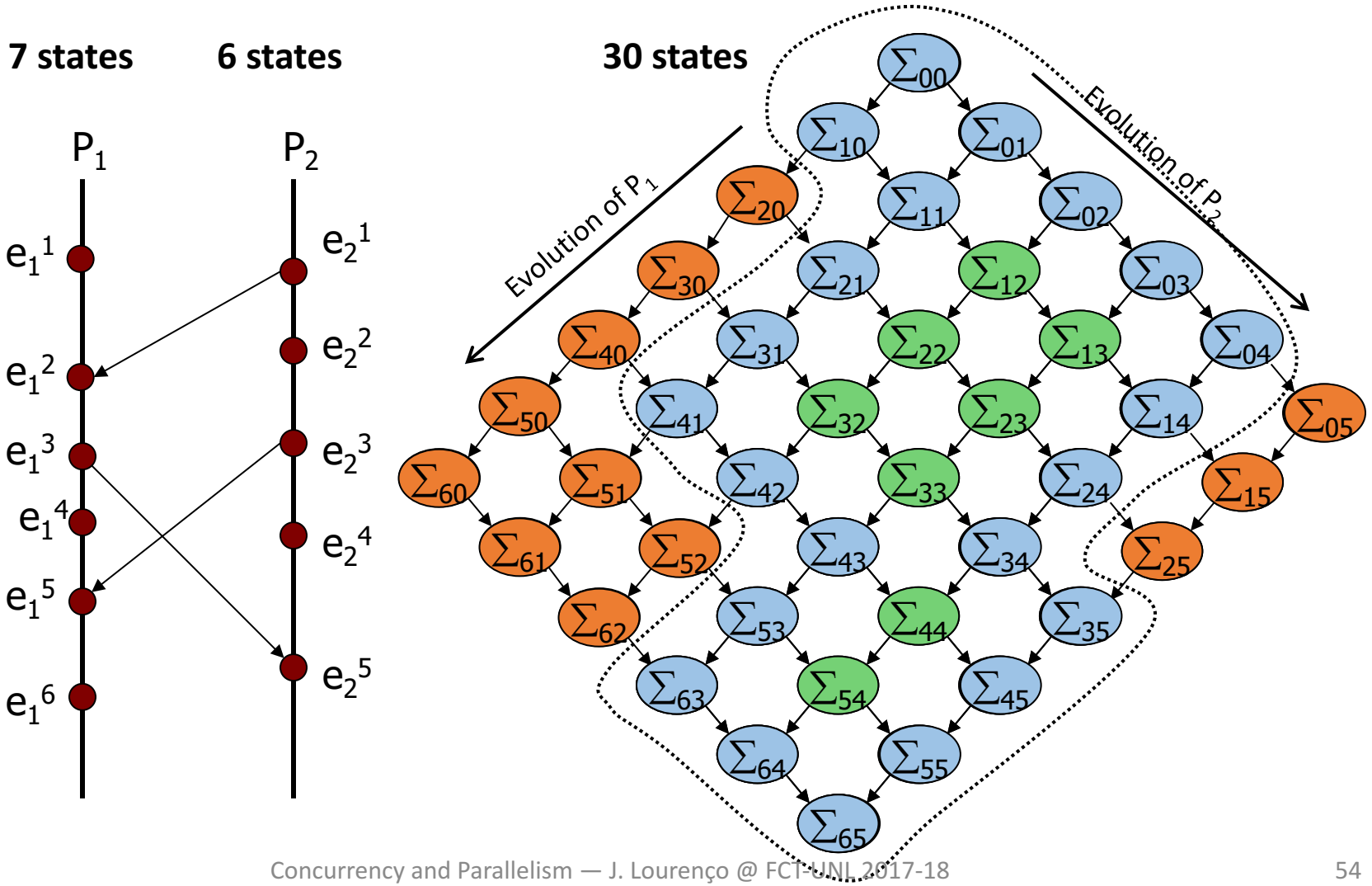
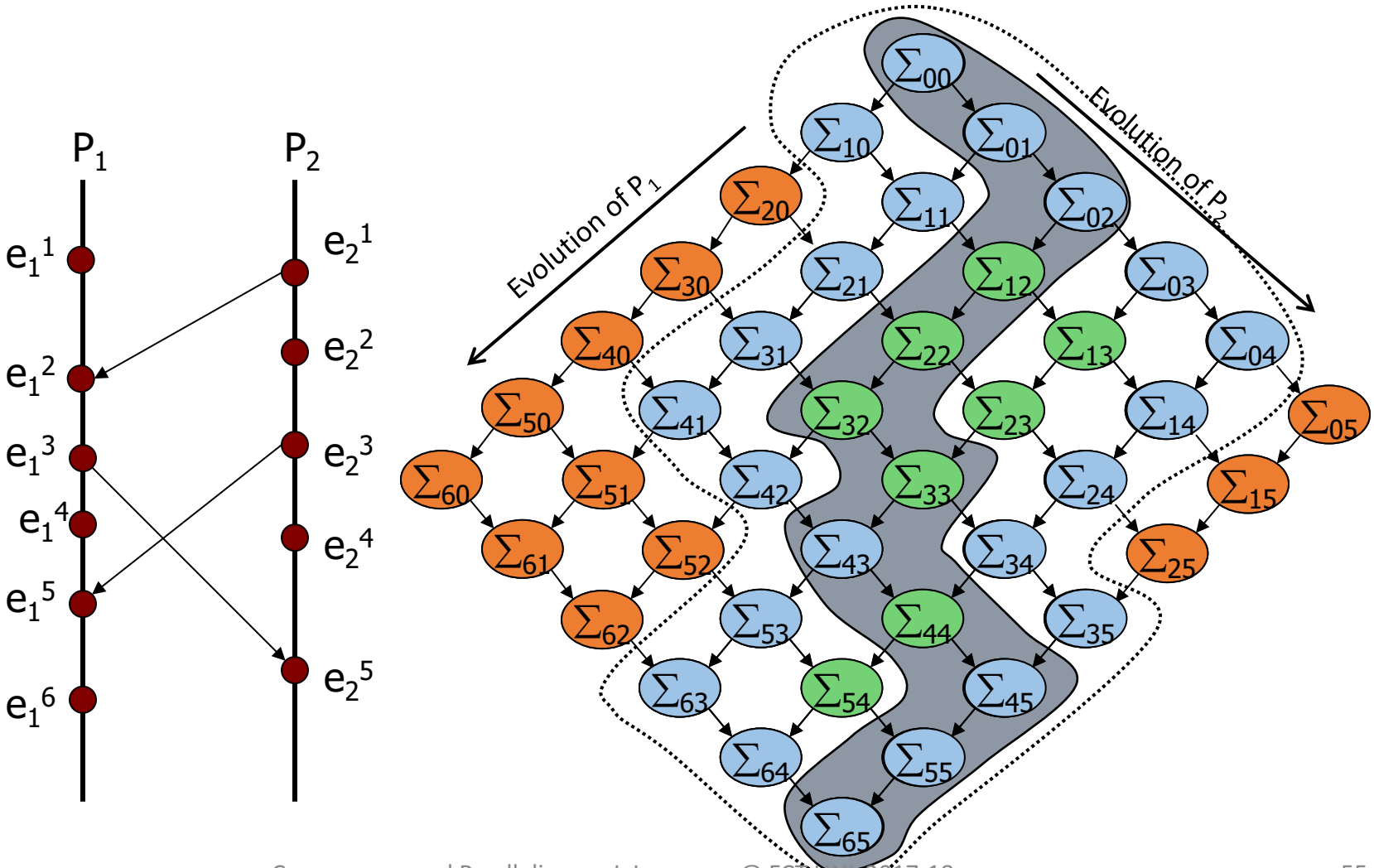


Consistent run



Concurrency Errors

Common Concurrency Errors

- Data races (atomicity violations)
- Ordering violations
- Unintended sharing
- High-level atomicity violations
- Deadlocks and livelocks

Data Race

- Code is supposed to execute atomically
  - Multiple dependent instructions to manipulate some data
- Interleaving with instructions of another thread that access the same data

Thread 1

```
void Bank::Deposit(int a)
{
    int t = bal;
    bal = t + a;
}
```

Thread 2

```
void Bank::Withdraw(int a)
{
    int t = bal;
    bal = t - a;
}
```

Data Race

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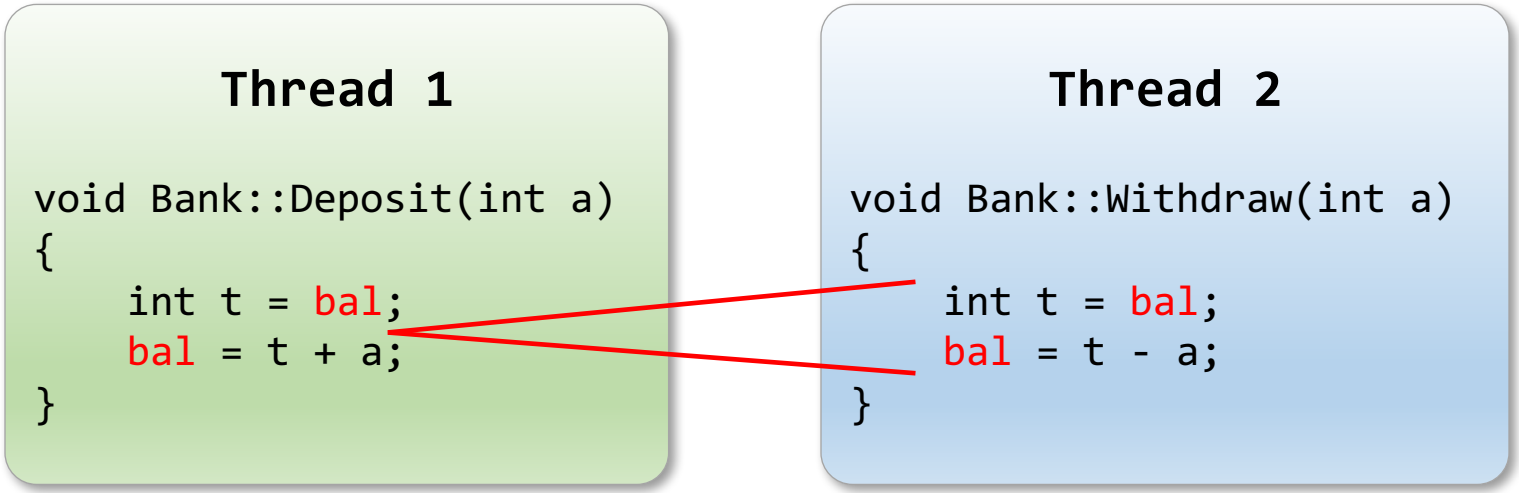

The widthdraw is not reflected in the final balance!

Ordering Violation

- Missing or incorrect synchronization between two processes
  (e.g., a producer and a consumer)

Thread 1

```
work = null;
CreateThread (Thread 2);
work = new Work();
```

Thread 2

```
ConsumeWork( work );
```

Ordering Violation

- Missing or incorrect synchronization between two processes
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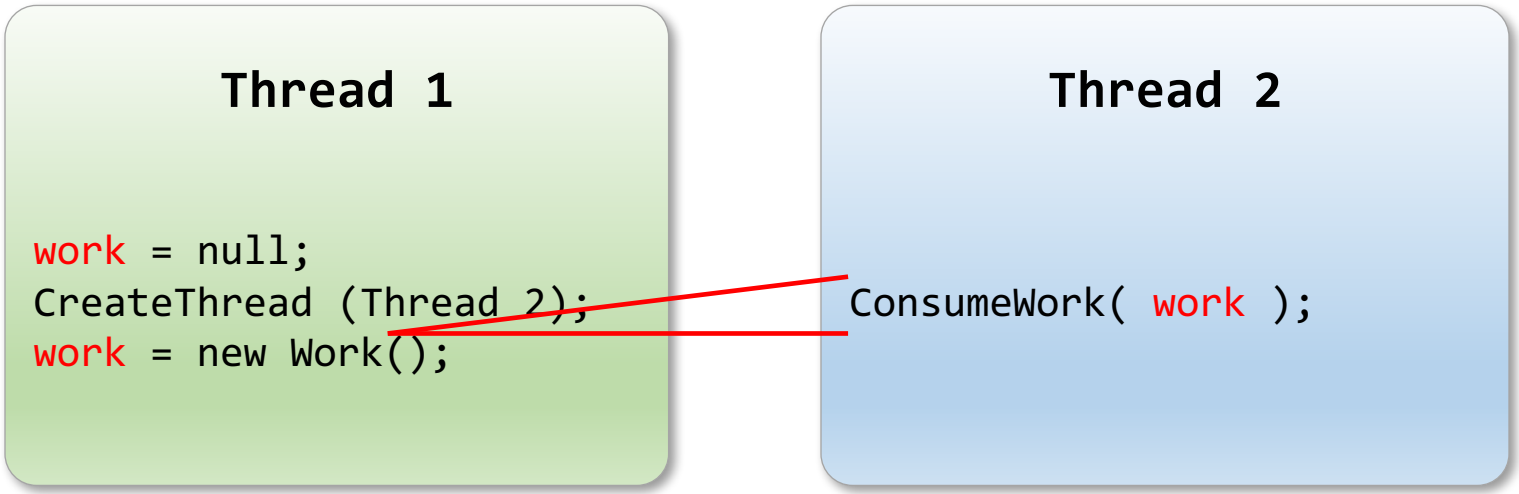


'work' is not initialized yet!

Unintended Sharing

- Processes accidentally share data
  - 'work()' is executed by both threads concurrently

```
void work() {
   static int local = 0;
   …
   local += …
   …
}
```

Thread 1

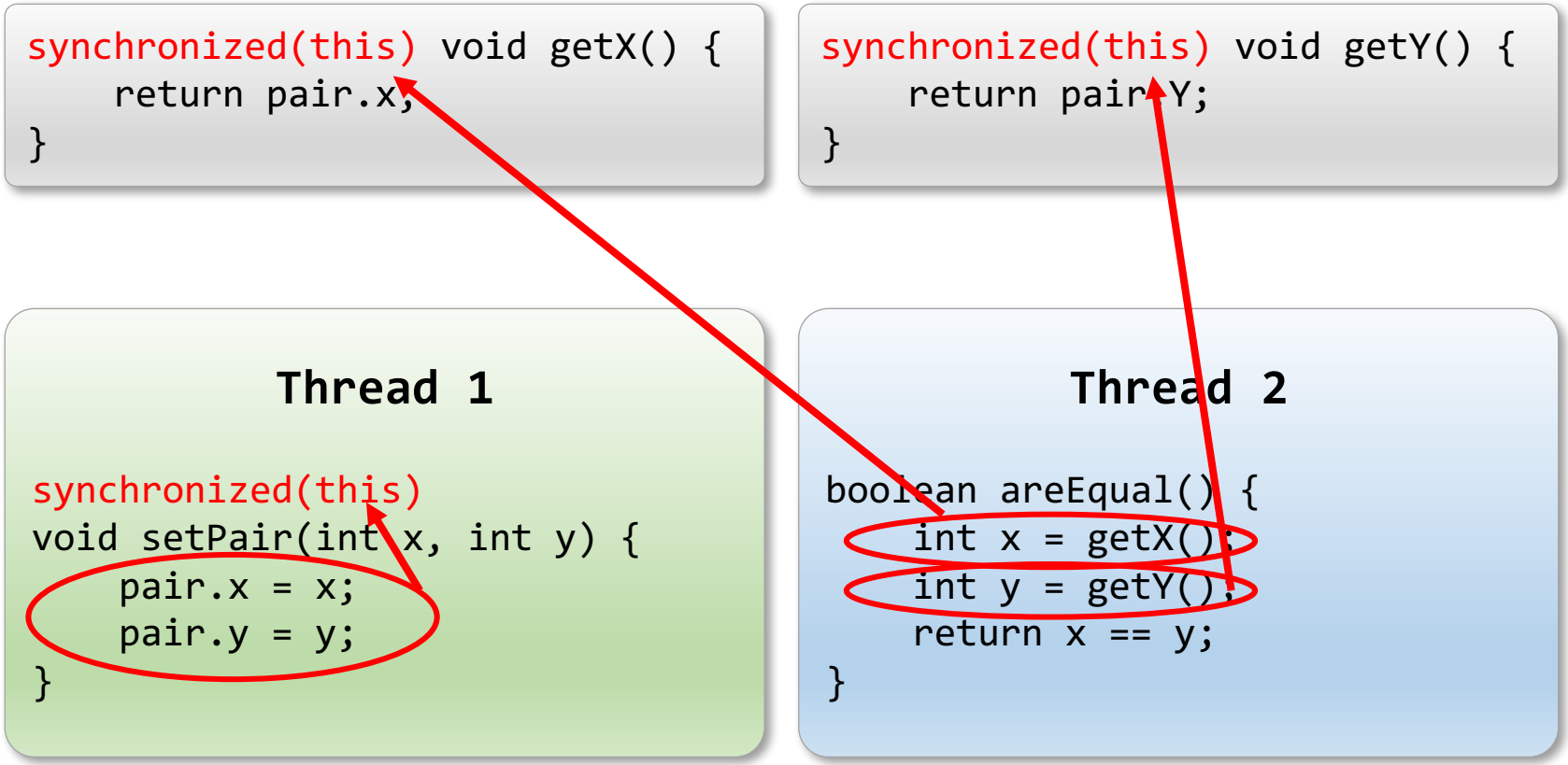
```
…
work()
…
```

Thread 2

```
…
work()
…
```

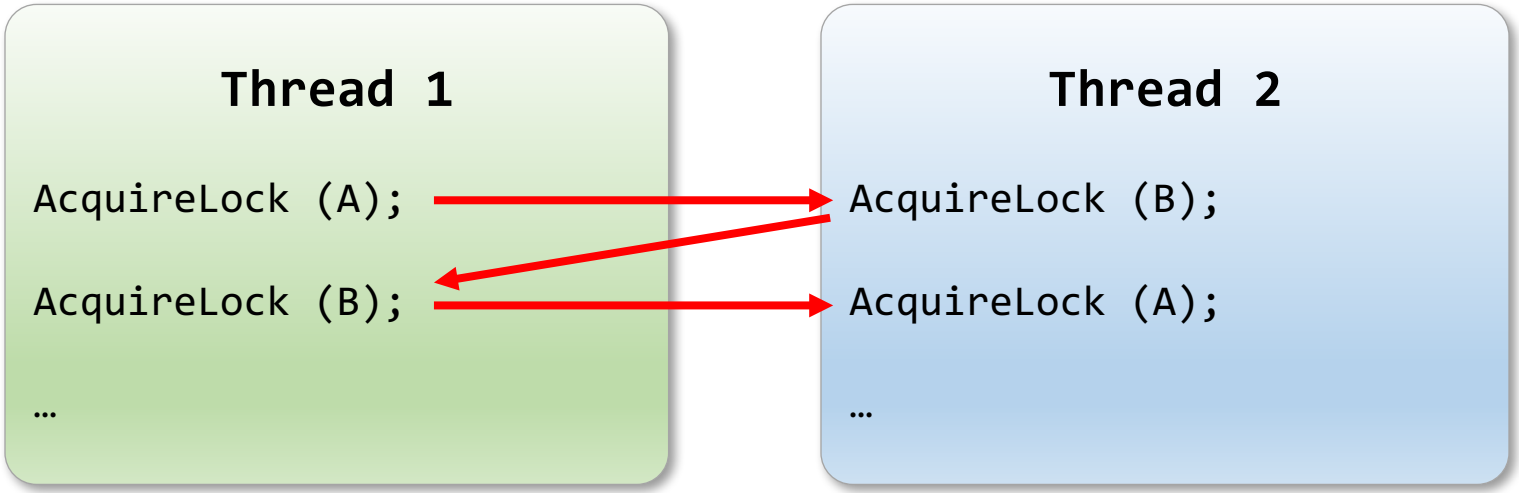
High-Level Data Race

- Wrongly defined atomic blocks



Deadlock

- Processes are waiting forever for each other



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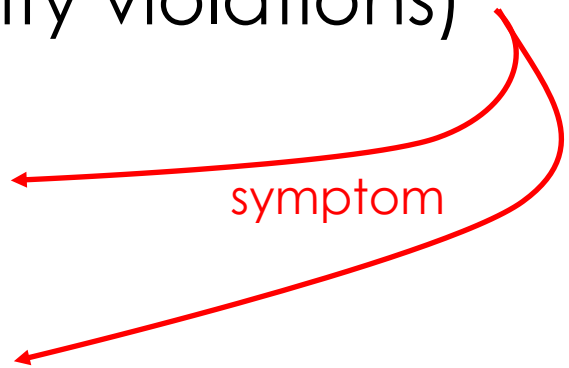

Common Concurrency Errors

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Concurrency Errors

Data Races

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- Two conflicting memory accesses happening concurrently
- Which means:
  - They access the same memory location
  - At least one is an update (write)

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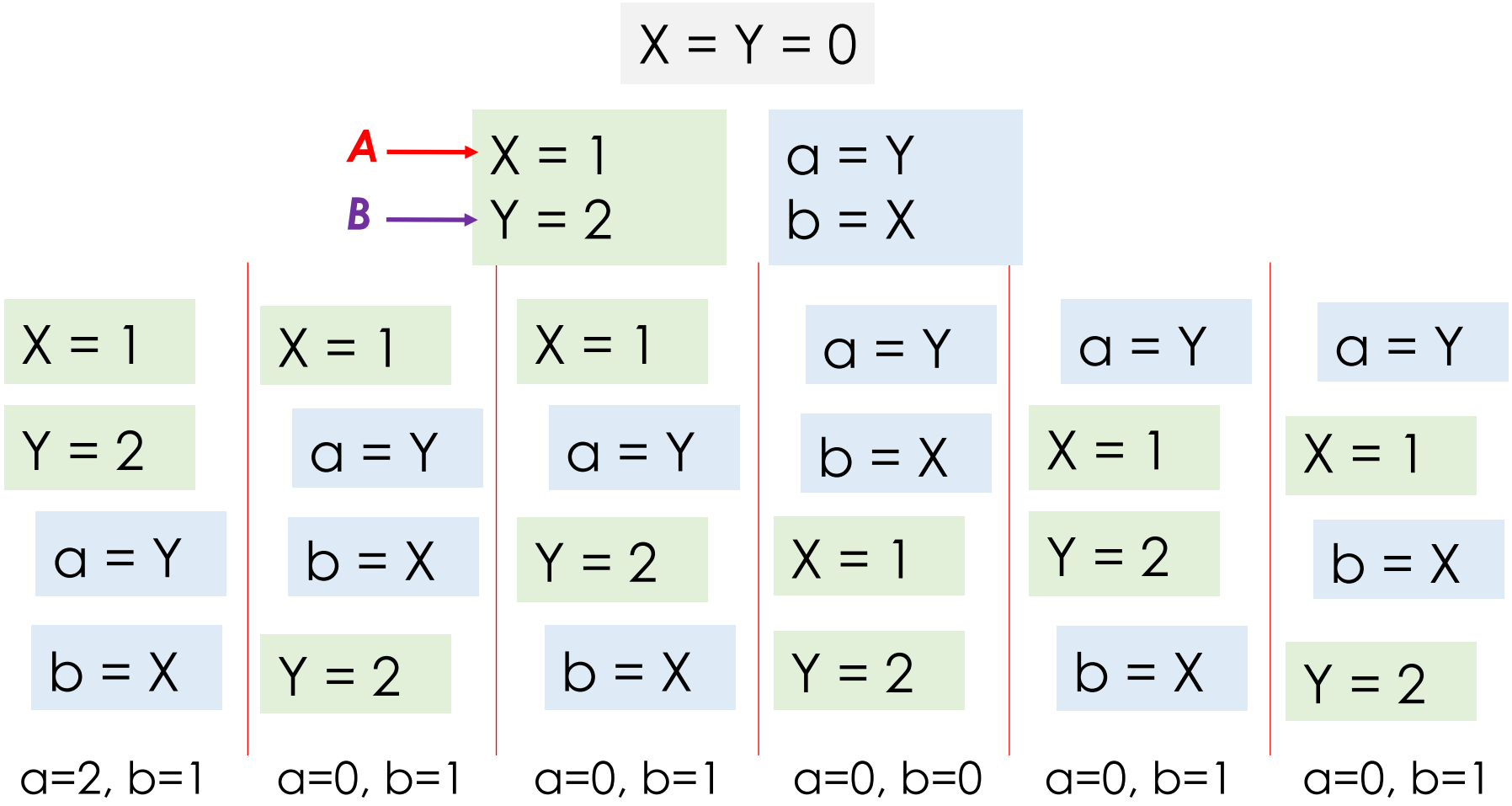
- Write — Write
- Write — Read
- Read — Write
- Read — Read

What means "Happens Concurrently"?

- Two events A and B happen concurrently if both
  A, B
  and
  B, A
  are possible sequentially consistent executions of those events

Assigning Semantics to Concurrent Programs



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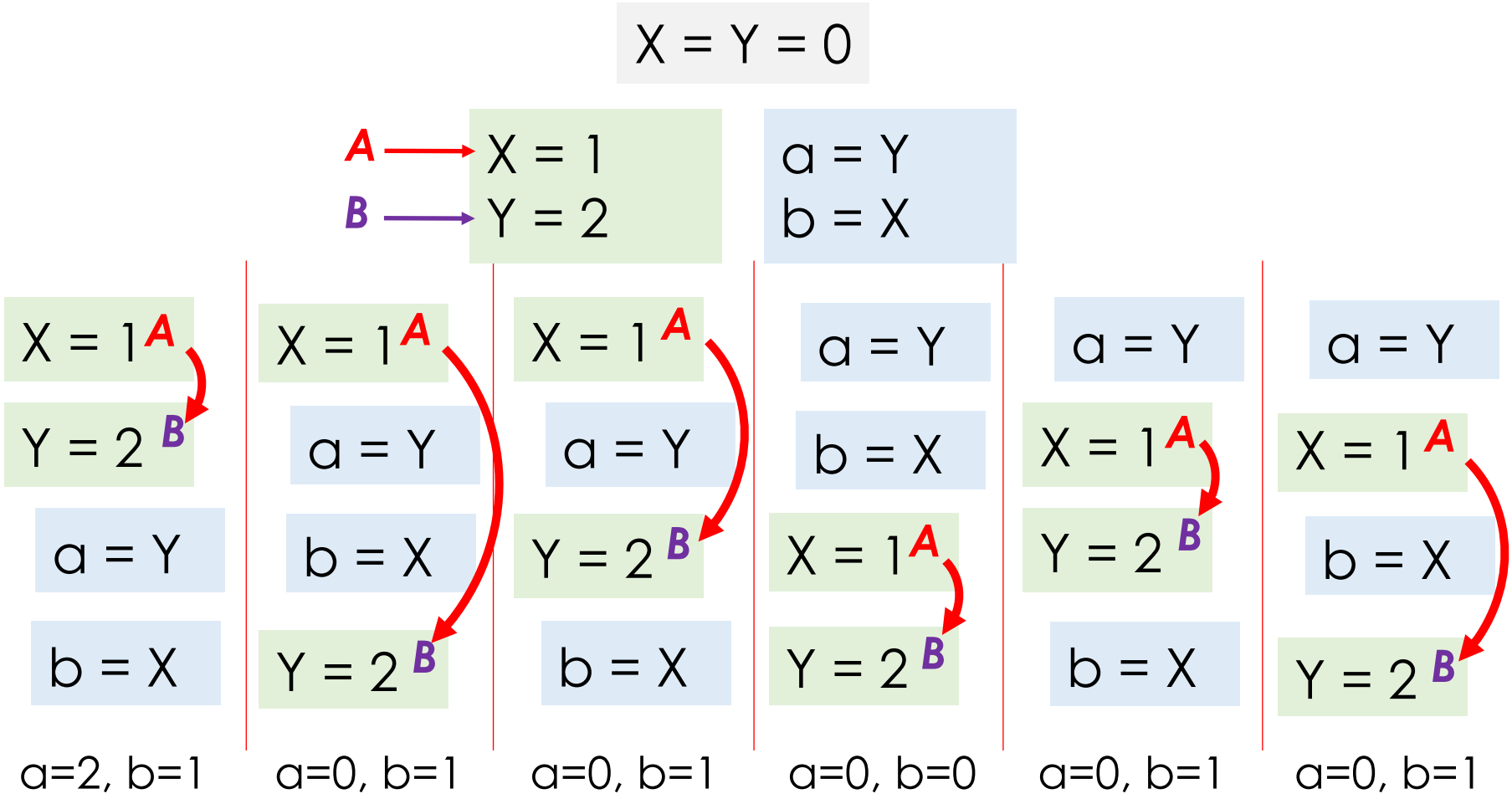
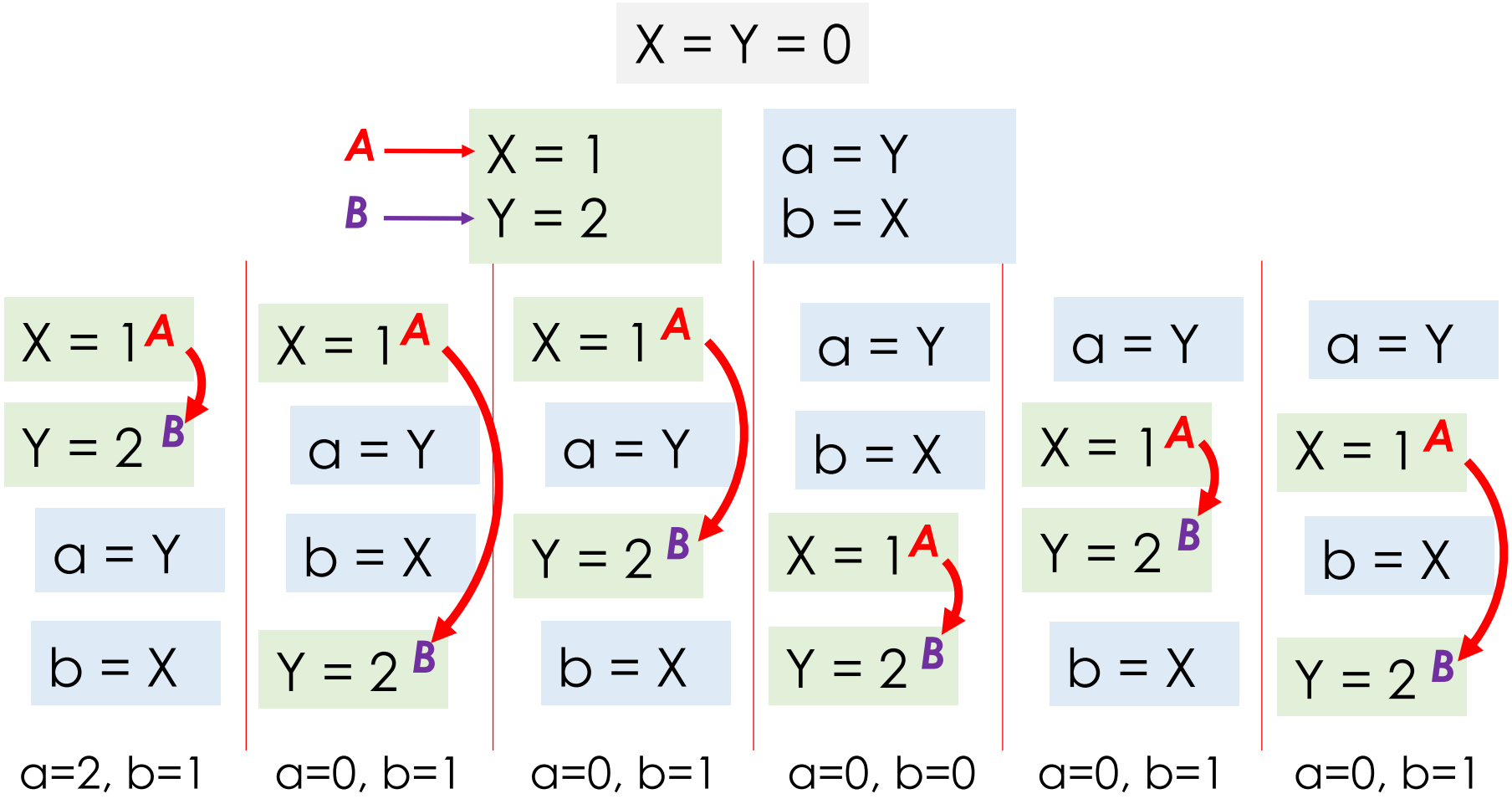
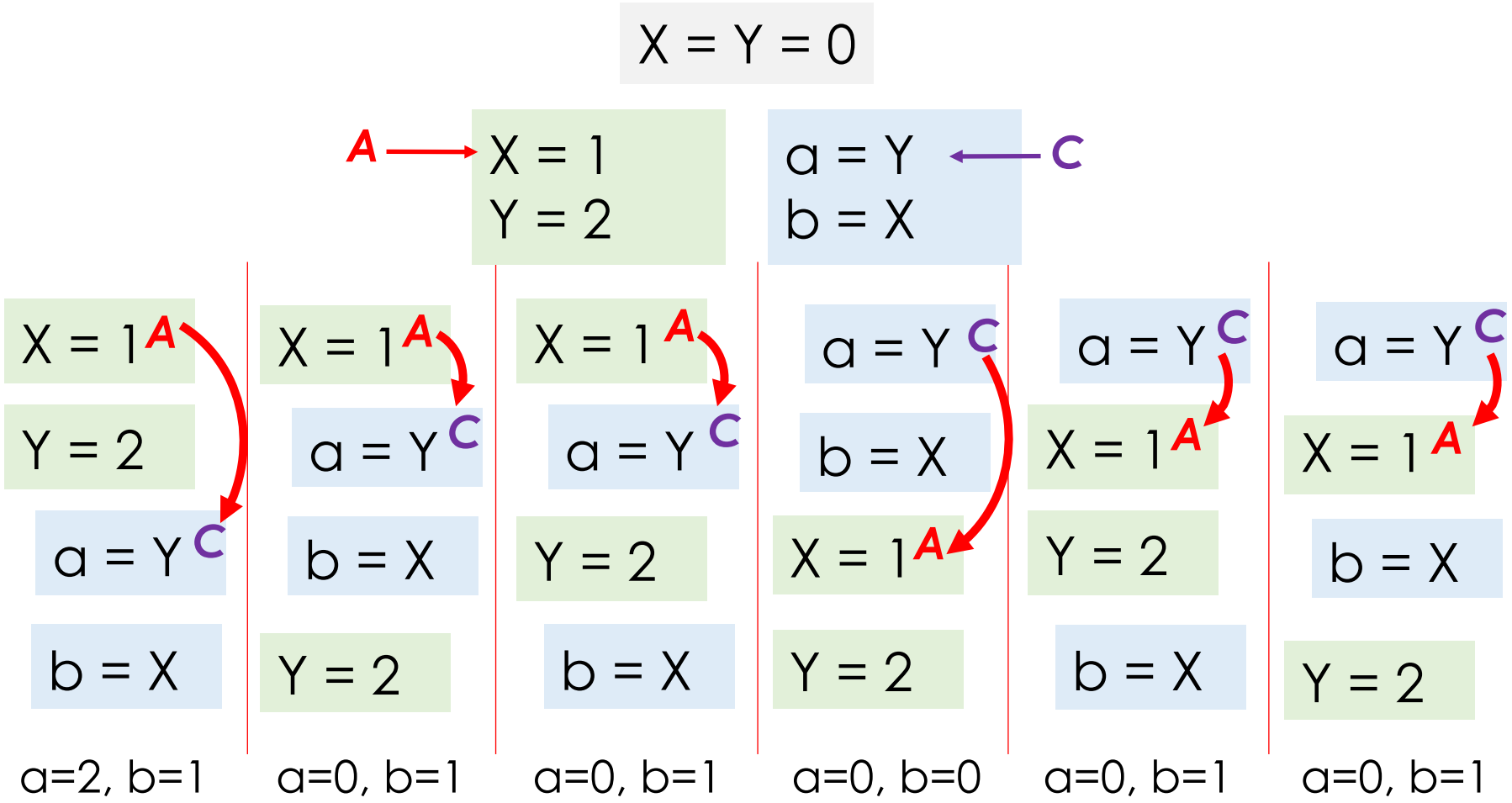


Assigning Semantics to Concurrent Programs



Always "A, B". Events 'A' and 'B' ***are not*** *concurrent!*

Assigning Semantics to Concurrent Programs



Both "A, C" and "C, A". Events 'A' and 'C' ***are*** *concurrent!*

Question

'**x**' is a shared variable, initially 0

Q: Knowing that processes A and B execute concurrently, what are the possible values for 'x' after both processes terminate?

Any value in the range 5 to 10! ***Wrong!!!***

Process A

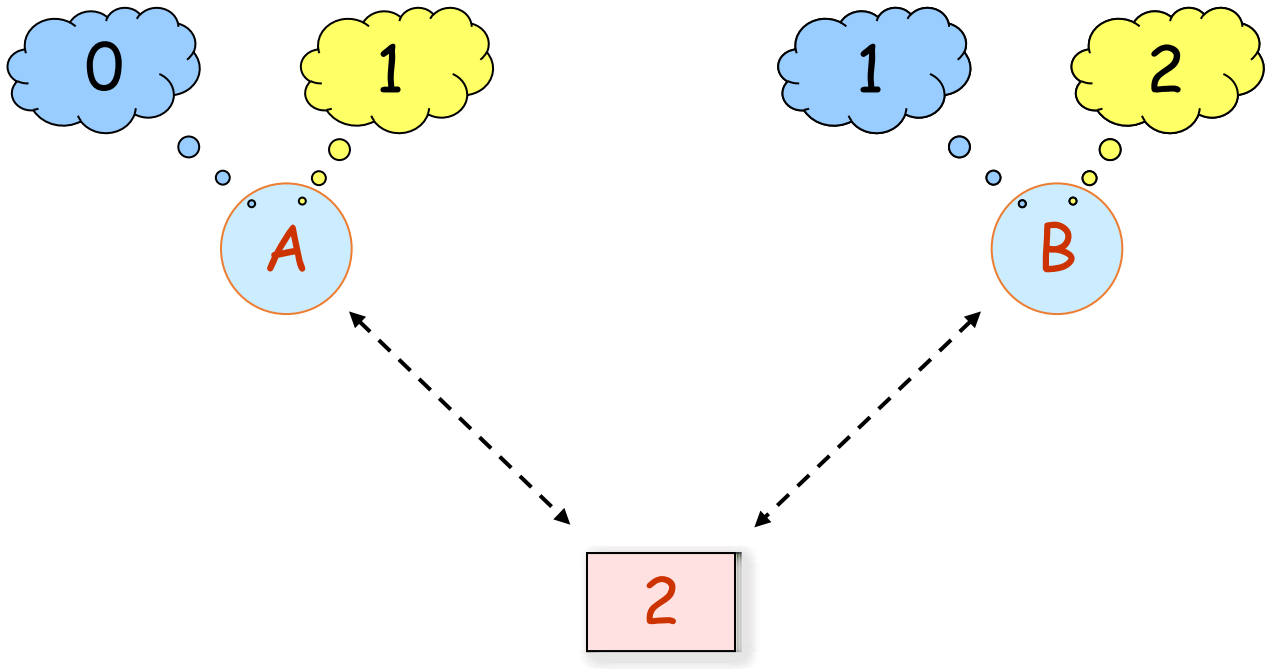
```
for (i = 0; i < 5;  i++) {
    x = x + 1
}
```

Process B

```
for (j = 0; j < 5;  j++) {
    x = x + 1
}
```

Any value in the range 2 to 10! ***How???***

The smallest value is 2



How to Detect a Data Race?

- Two concurrent accesses to a shared memory location
- At least one of them is a write

- How to monitor memory accesses?
- How to detect if two accesses are (or may be) concurrent?

Acknowledgments

- Some parts of this presentation was based in publicly available slides and PDFs
  - www.cs.cornell.edu/courses/cs4410/2011su/slides/lecture10.pdf
  - www.microsoft.com/en-us/research/people/madanm/
  - williamstallings.com/OperatingSystems/
  - codex.cs.yale.edu/avi/os-book/OS9/slide-dir/

The END