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

Concurrency Errors (1)

lecture 21 (2020-05-13)

Master in Computer Science and Engineering

— Concurrency and Parallelism / 2019-20 —

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Agenda

- Assigning Semantics to Concurrent Programs
- Concurrency Errors
  - Detection of data races
  - Detection of high-level data races and stale value errors
  - Detection of deadlocks
- Reading list:
  - TBD

Assigning Semantics to Concurrent Programs

Assigning Semantics to Concurrent Programs

X = Y = 0

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

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

Assigning Semantics to Concurrent Programs

```
X = Y = 0
```

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

```
X = 1
Y = 2
```

```
a = Y
b = X
```

- What are the final values for ’X’, ‘Y’, ‘a’ and ‘b’?

Assigning Semantics to Concurrent Programs

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X, Y => Global Vars
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```
X = 1
Y = 2
```

```
a = Y
b = X
```

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

Assigning Semantics to Concurrent Programs

```
X = Y = 0
```

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

```
X = 1
Y = 2
```

```
a = Y
b = X
```

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

Assigning Semantics to Concurrent Programs

```
X = Y = 0

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

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

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

Assigning Semantics to Concurrent Programs

```
X = Y = 0
```

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

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

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

Assigning Semantics to Concurrent Programs

X = Y = 0

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

```
X = 1
Y = 2
```

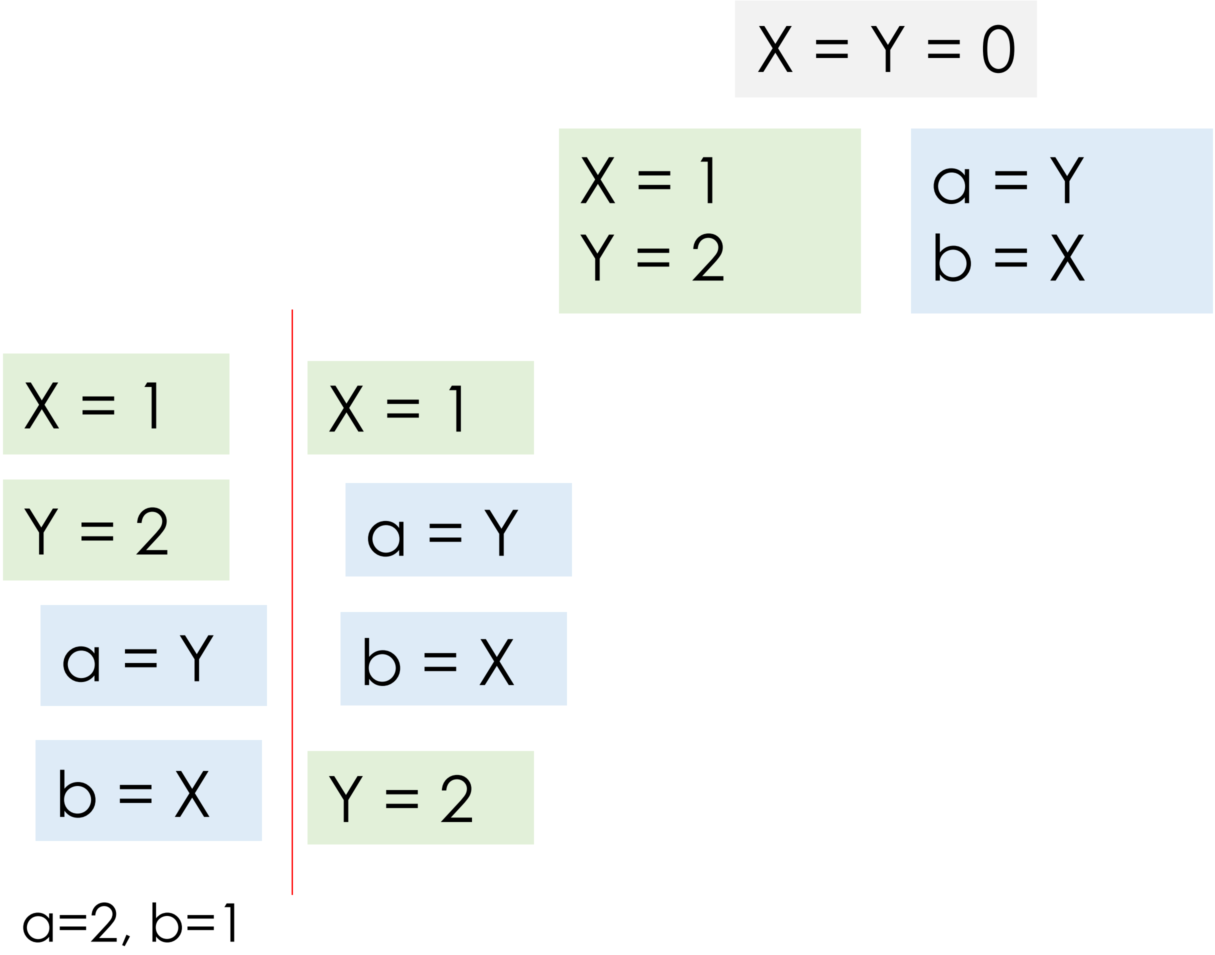
```
a = Y
b = X
```

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

a=2, b=1

Assigning Semantics to Concurrent Programs

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



X = Y = 0

```
X = 1        a = Y
Y = 2        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

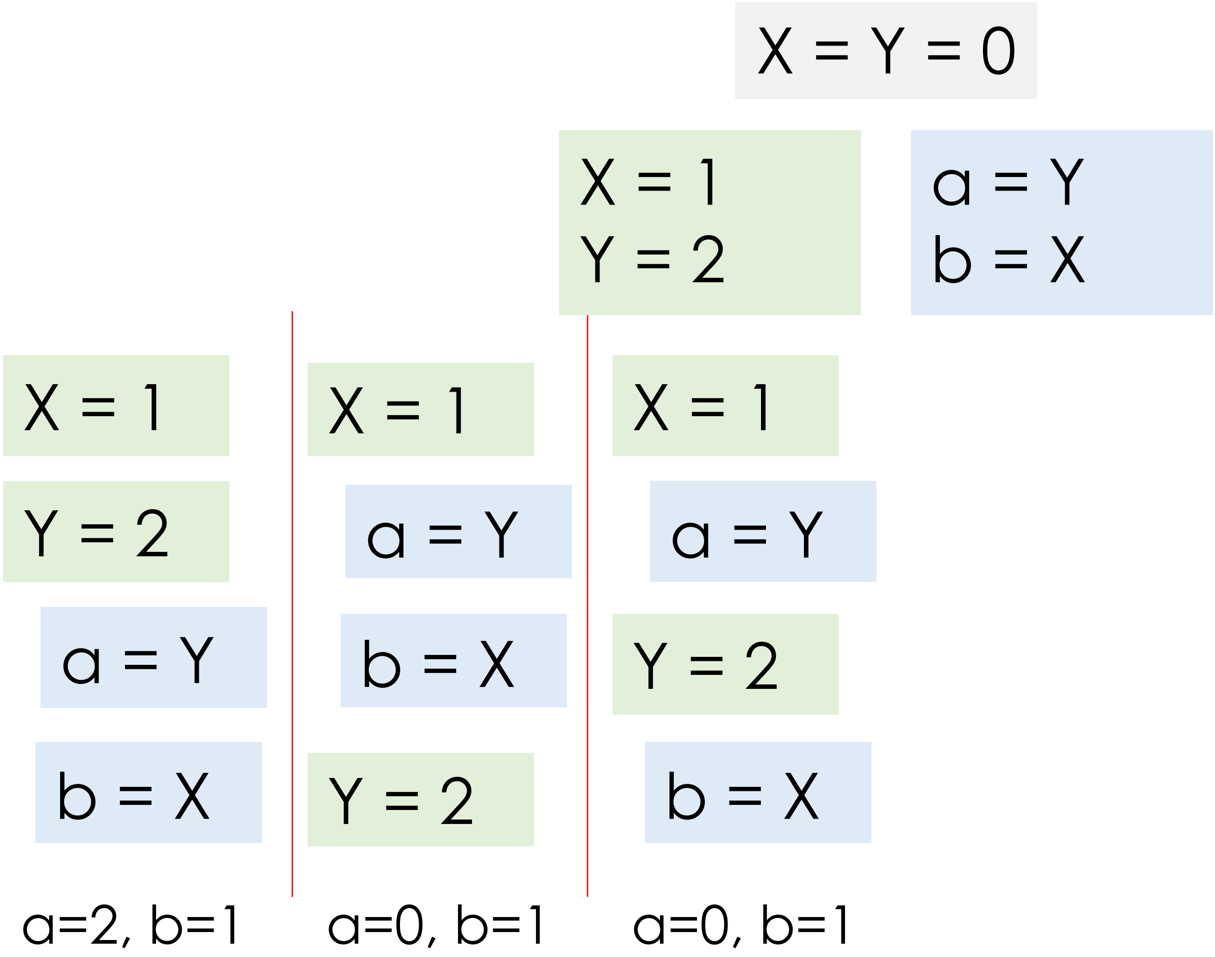
X, Y => Global Vars
a, b => Local Vars

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

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



```
X = Y = 0
```

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

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

a=2, b=1

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

a=0, b=1

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

a=0, b=1

Assigning Semantics to Concurrent Programs

X = Y = 0

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

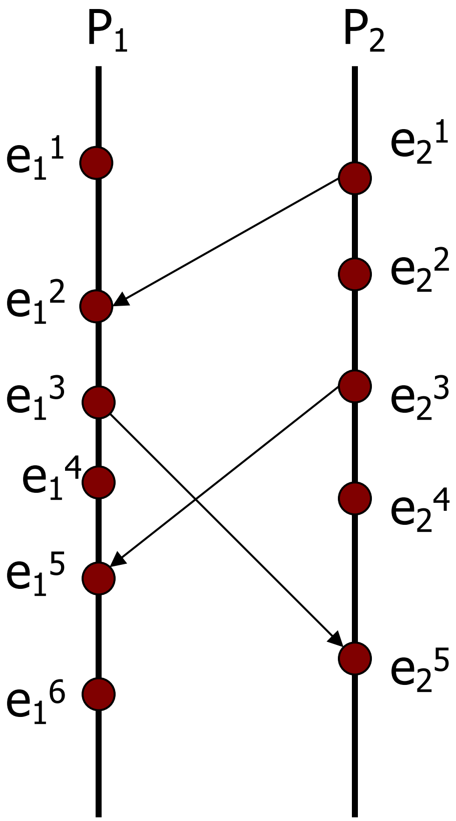
X = 1
Y = 2
	a = Y
	b = X

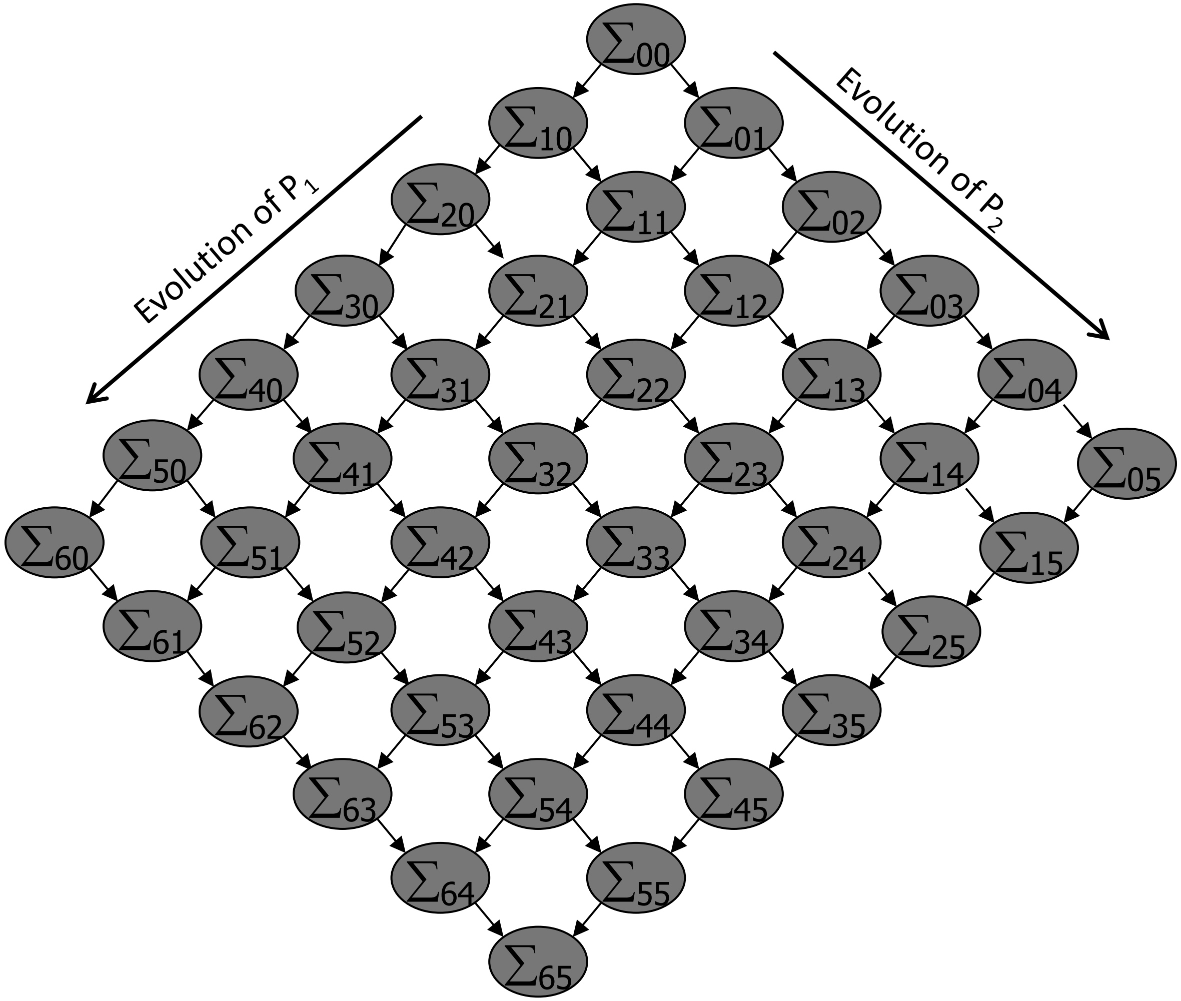
X = 1	X = 1	X = 1	a = Y	a = Y	a = Y
Y = 2	a = Y	a = Y	b = X	X = 1	X = 1
a = Y	b = X	Y = 2	X = 1	Y = 2	b = X
b = X	Y = 2	b = X	Y = 2	b = X	Y = 2
a=2, b=1	a=0, b=1	a=0, b=1	a=0, b=0	a=0, b=1	a=0, b=1

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
- Be aware that:
  - This is naturally true for sequential programs…
  - But it is not true for concurrent programs!

State explosion in concurrent programs





Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
Σ_{40} Σ_{31} Σ_{22} Σ_{13} Σ_{04}
Σ_{50} Σ_{41} Σ_{32} Σ_{23} Σ_{14} Σ_{05}
Σ_{60} Σ_{51} Σ_{42} Σ_{33} Σ_{24} Σ_{15}
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Σ_{63} Σ_{54} Σ_{45}
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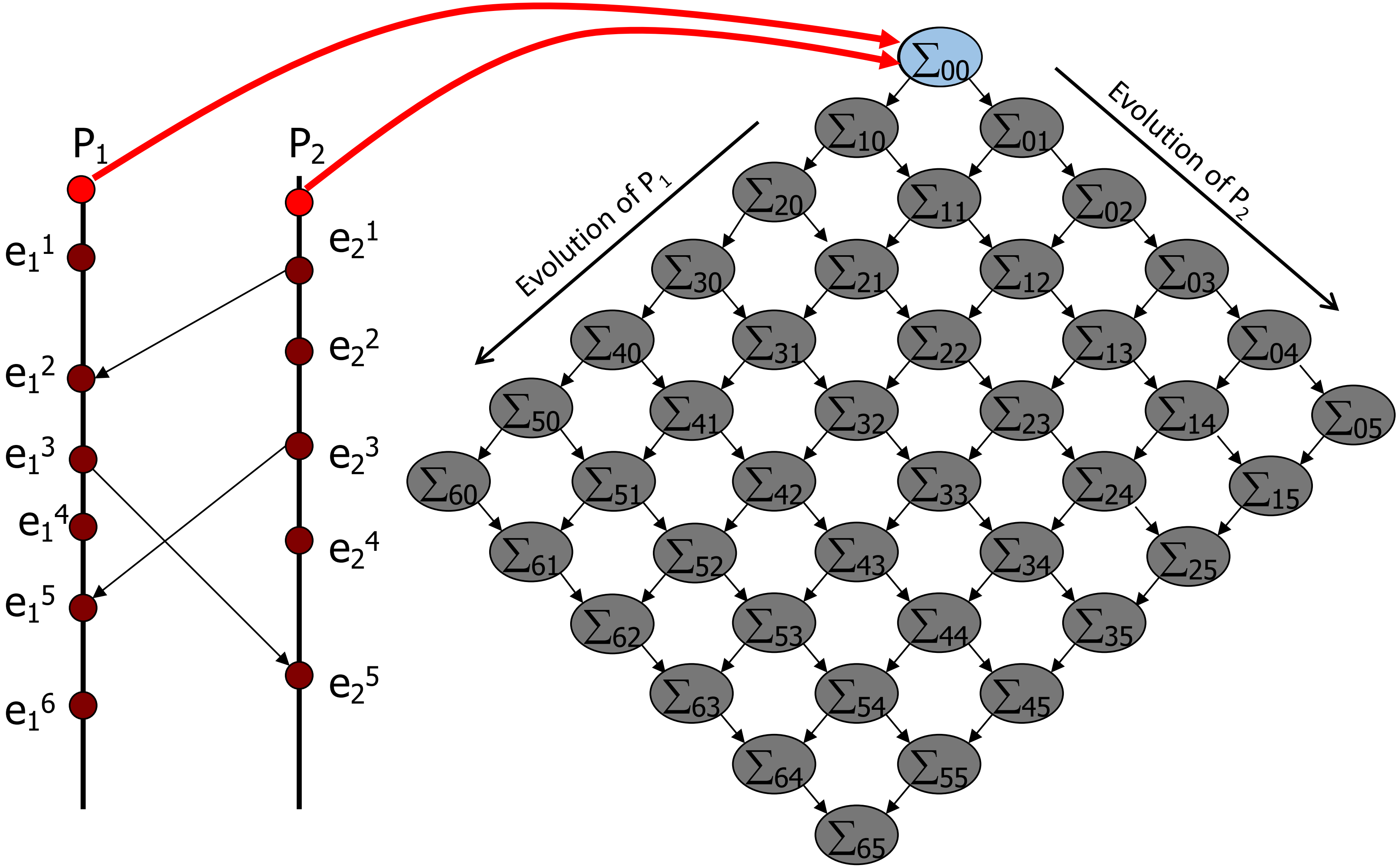
Σ_{65}

State explosion in concurrent programs



P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
Σ_{40} Σ_{31} Σ_{22} Σ_{13} Σ_{04}
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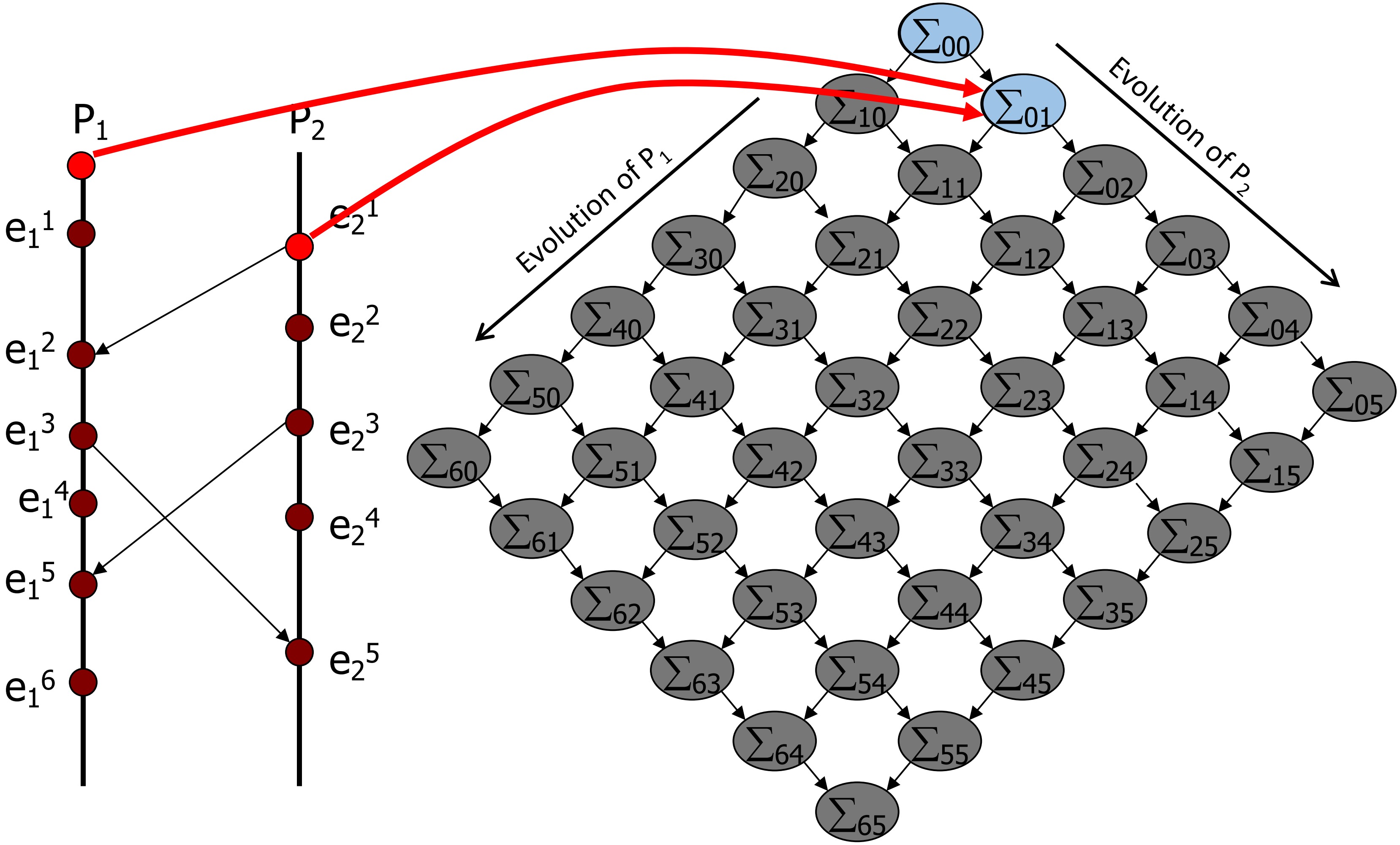
Σ_{64} Σ_{55}
Σ_{65}

State explosion in concurrent programs


P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
Σ_{00}
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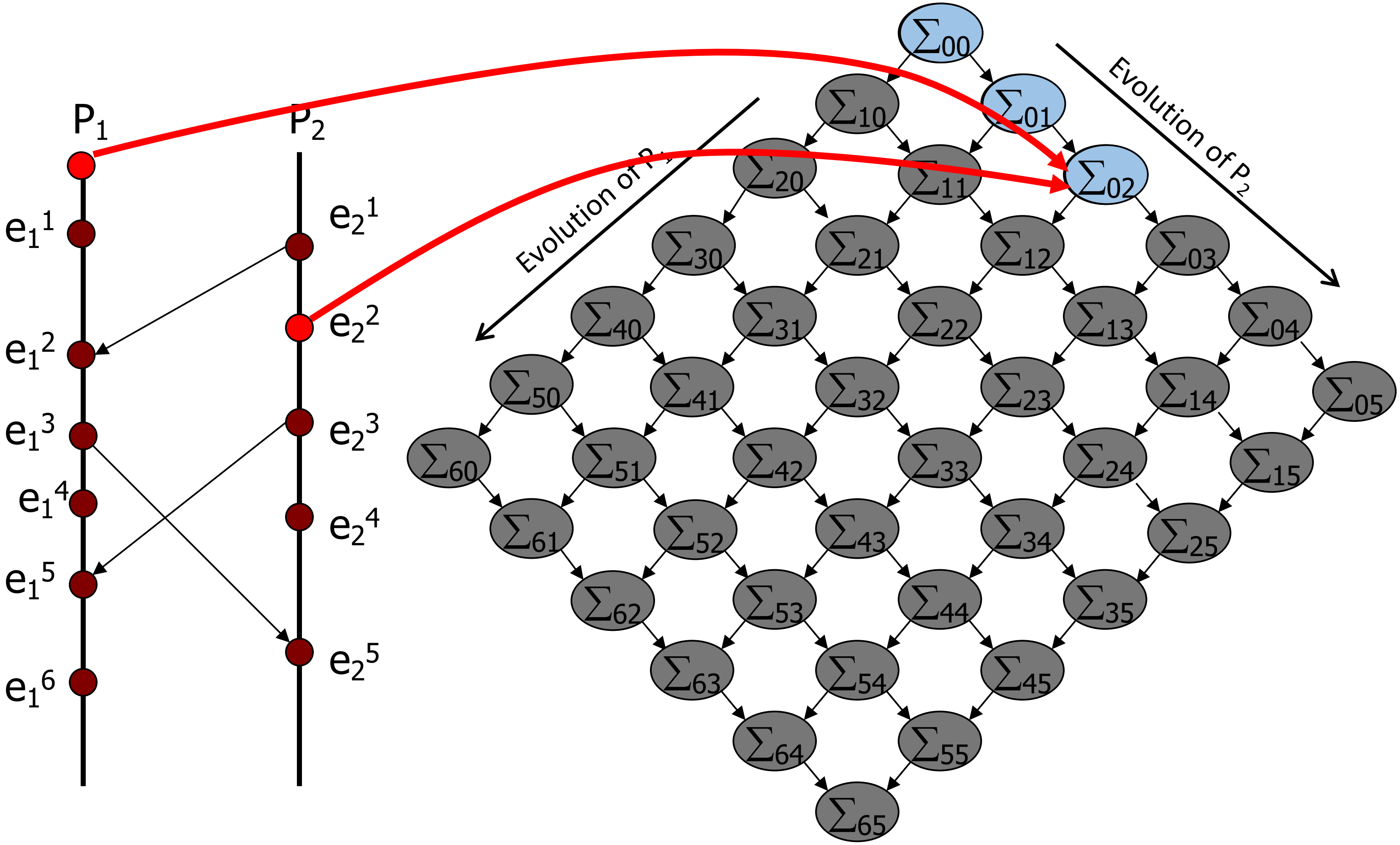
State explosion in concurrent programs



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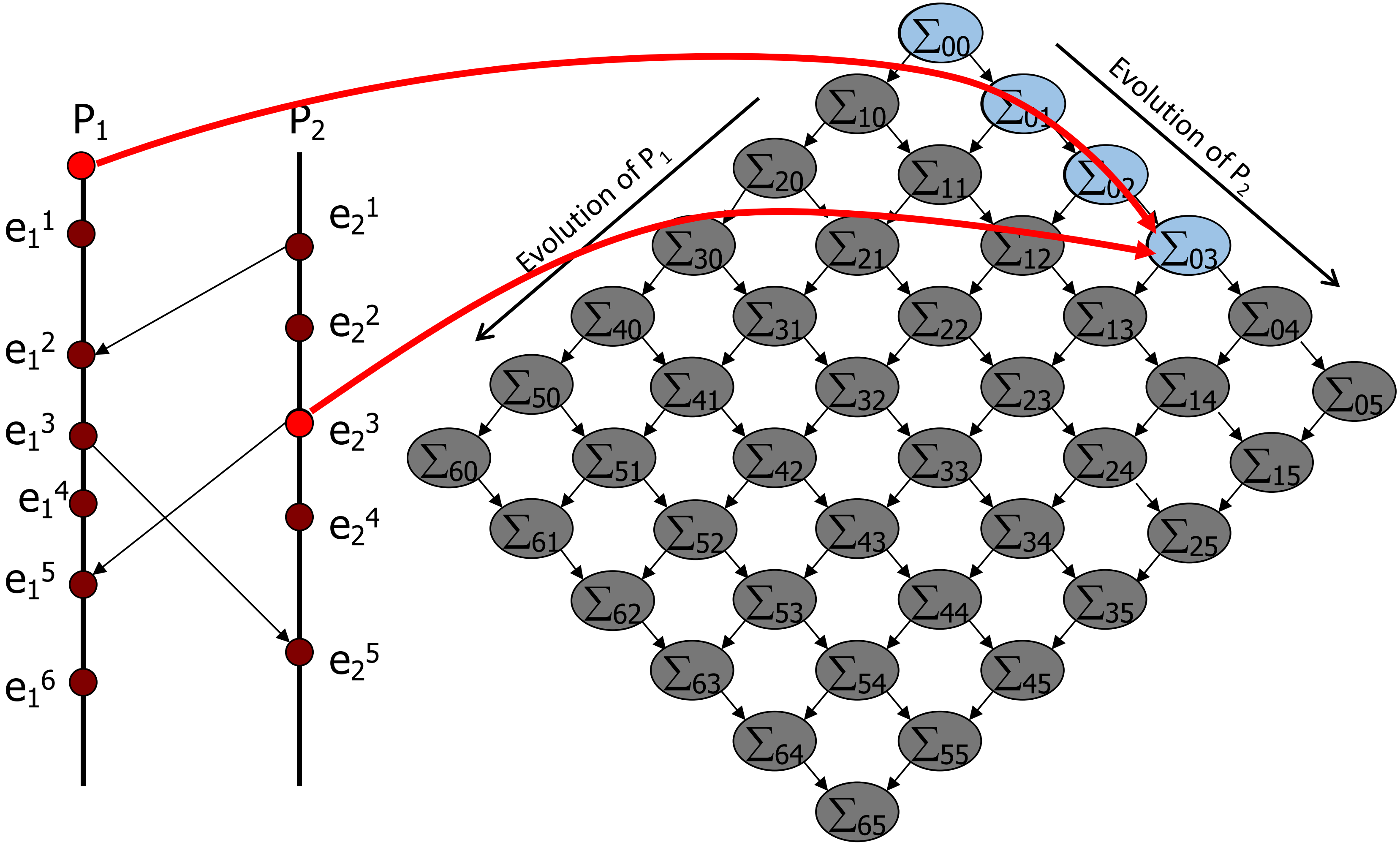

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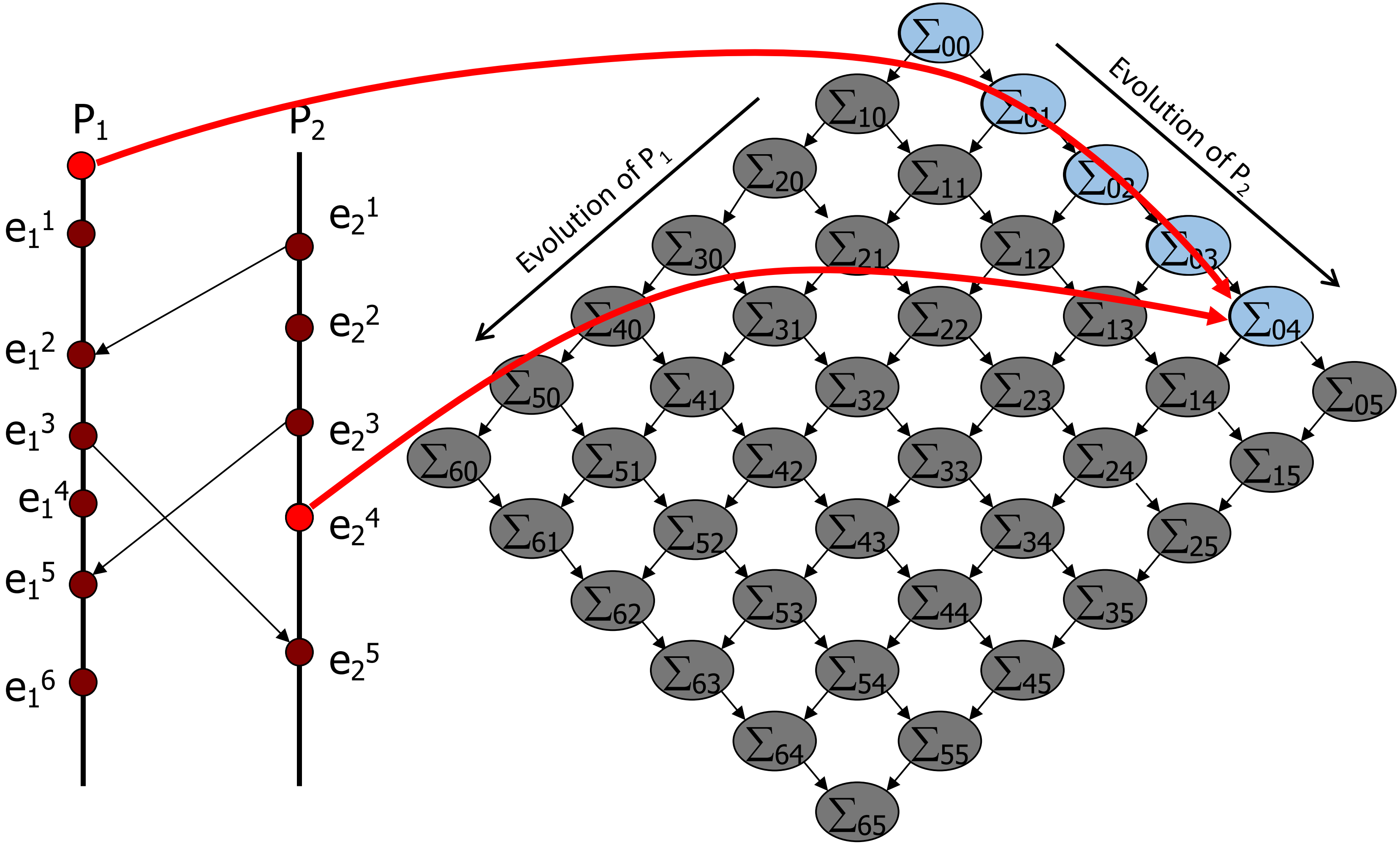
P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
Σ_{40} Σ_{31} Σ_{22} Σ_{13} Σ_{04}
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Σ_{64} Σ_{55}
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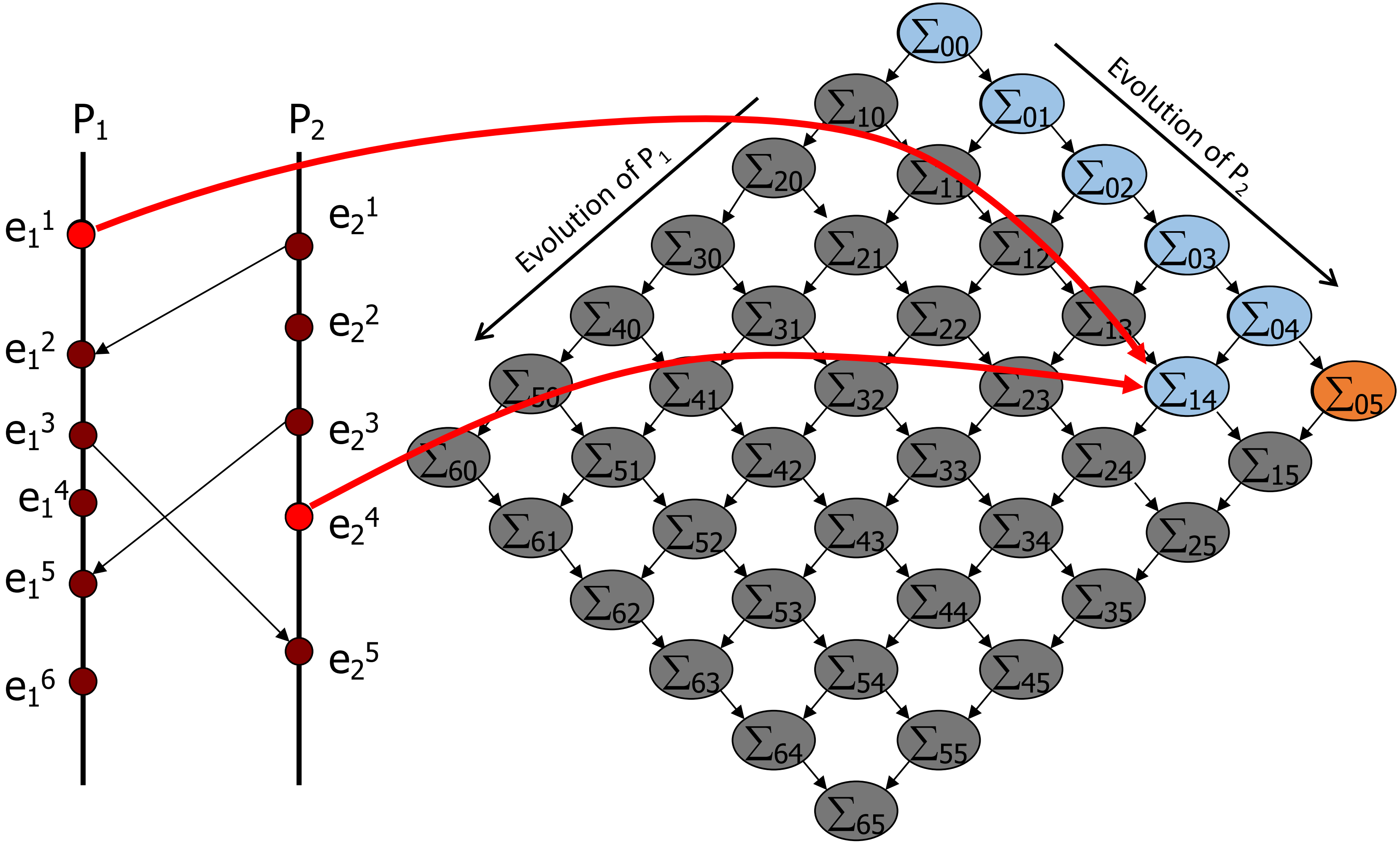

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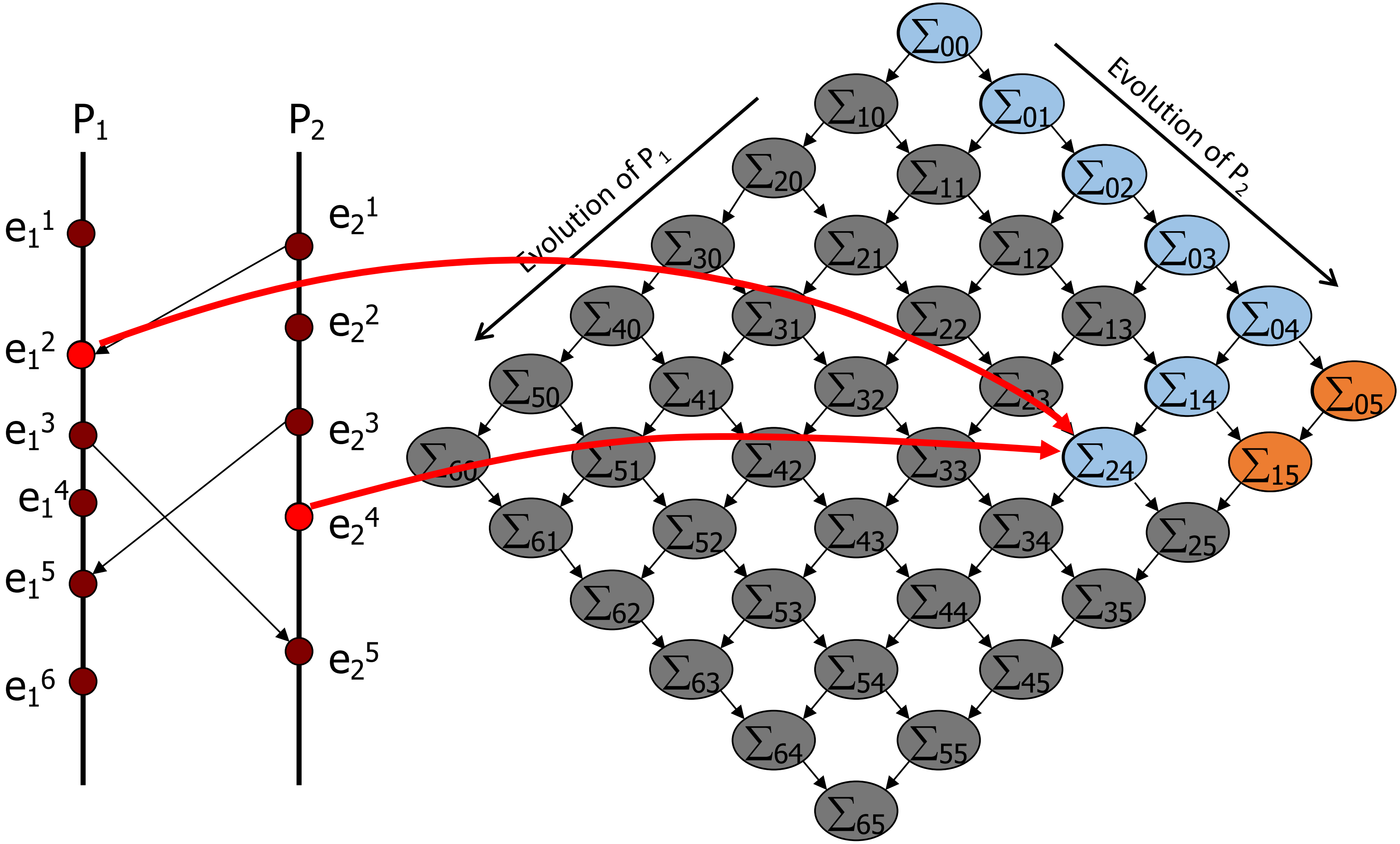

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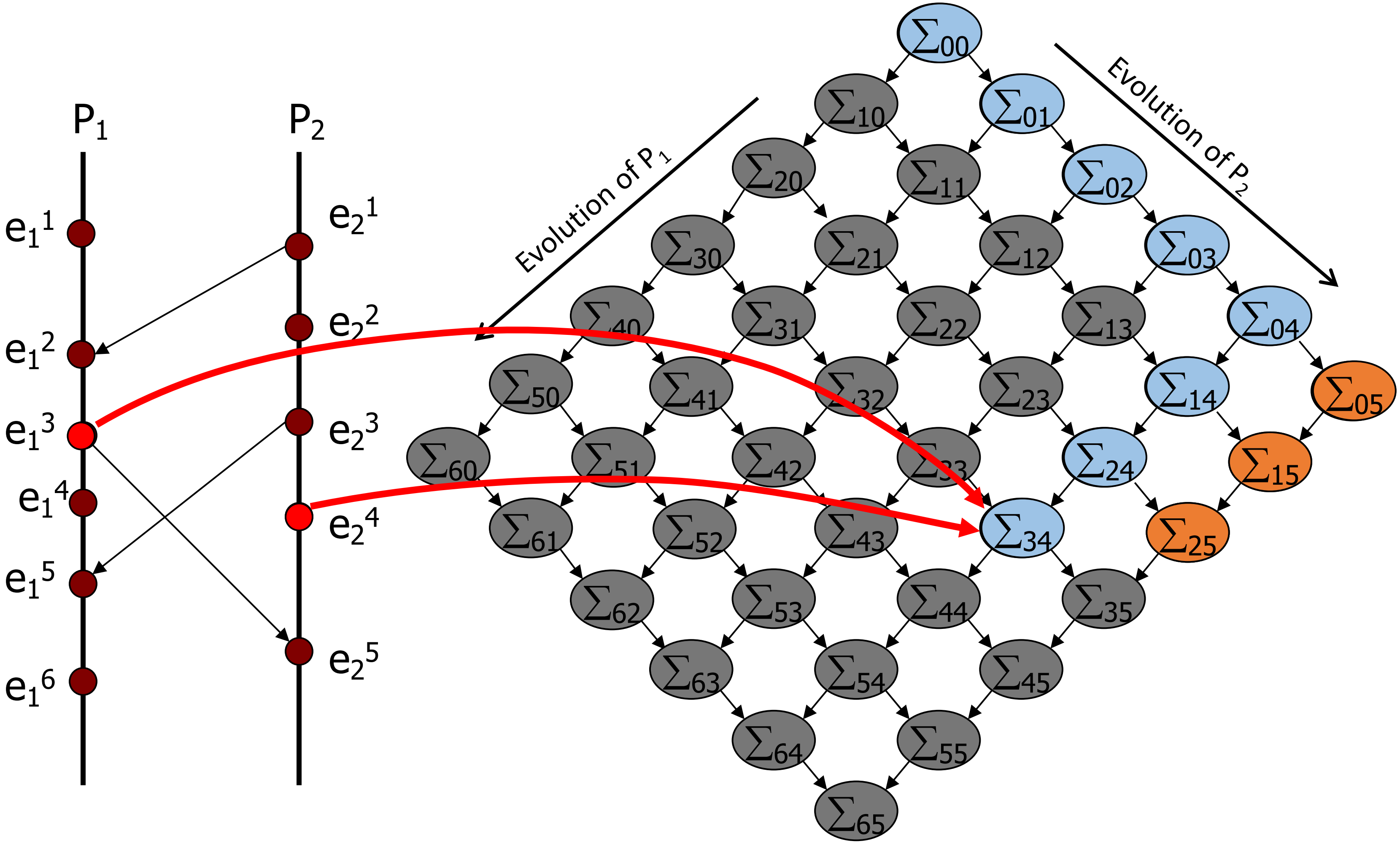

P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
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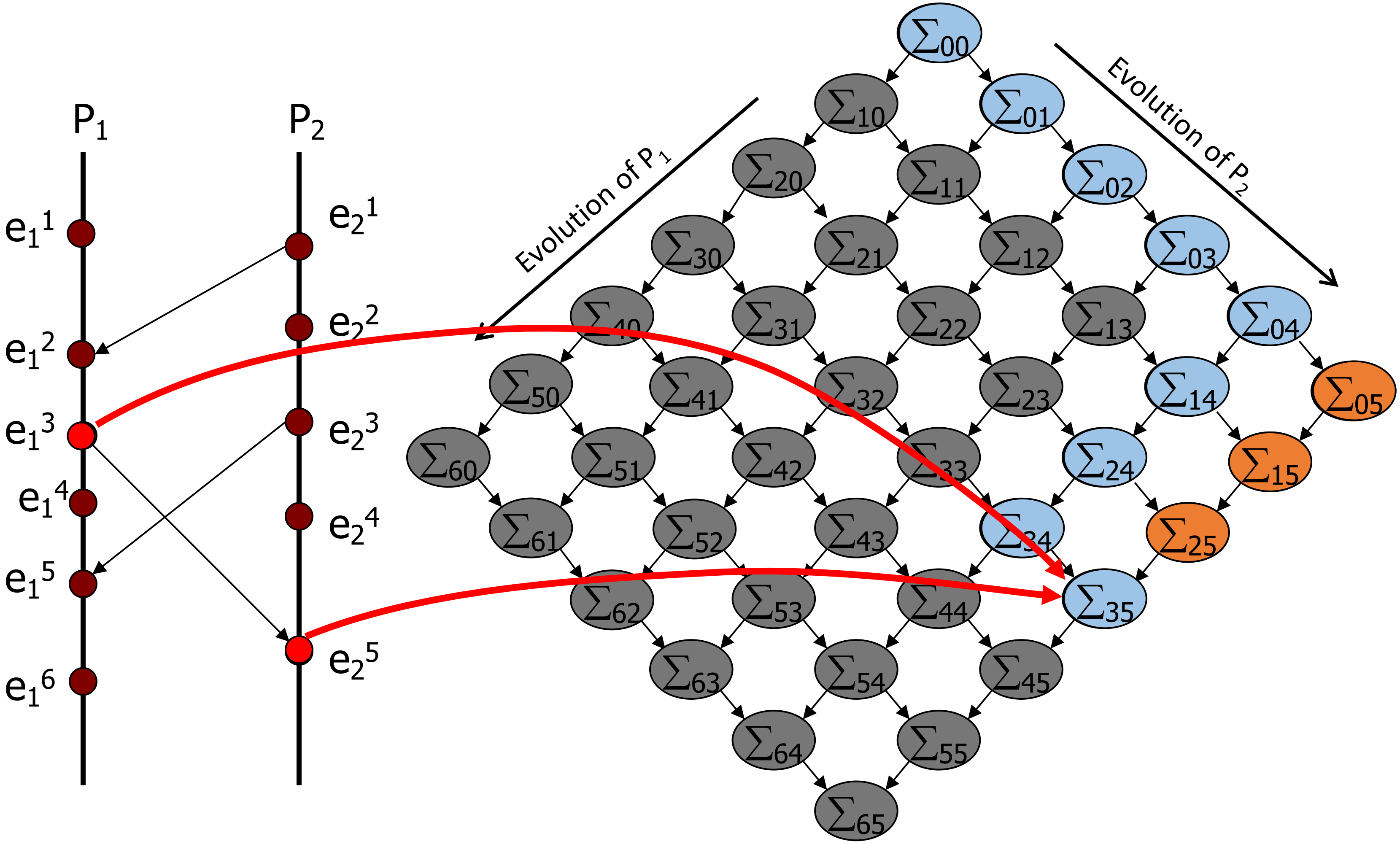
P_1
P_2
e_1^1
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e_2^1
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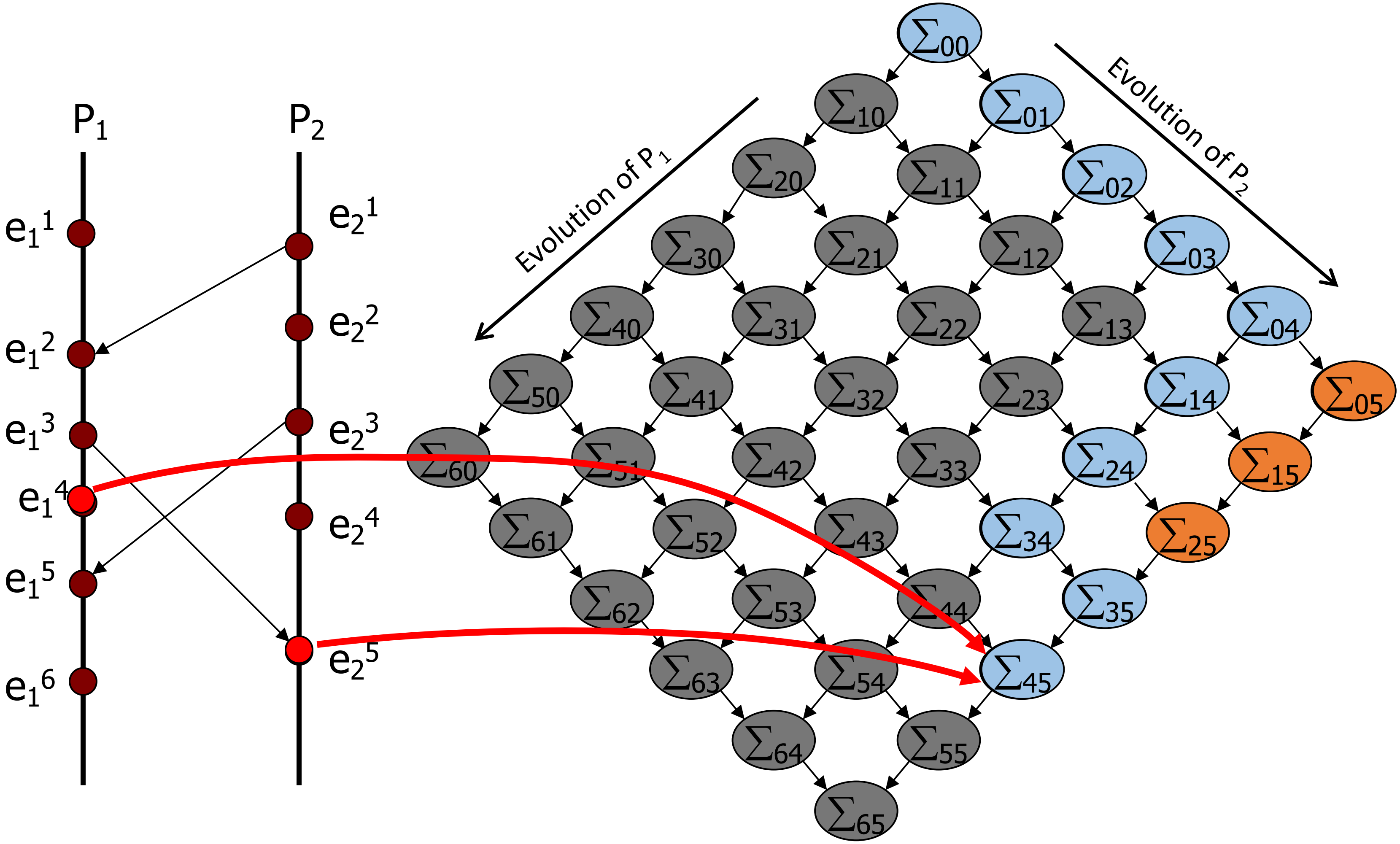
State explosion in concurrent programs



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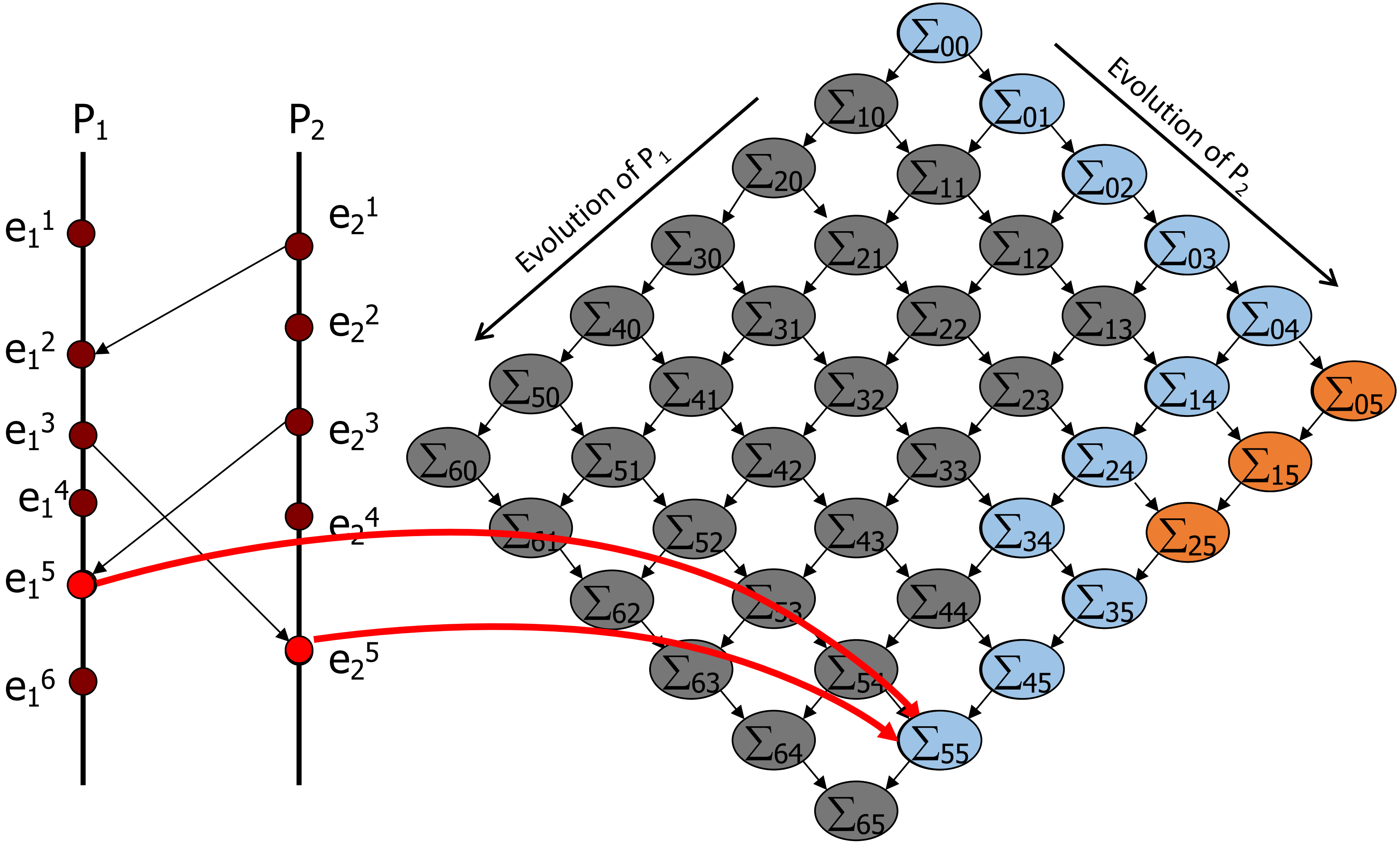

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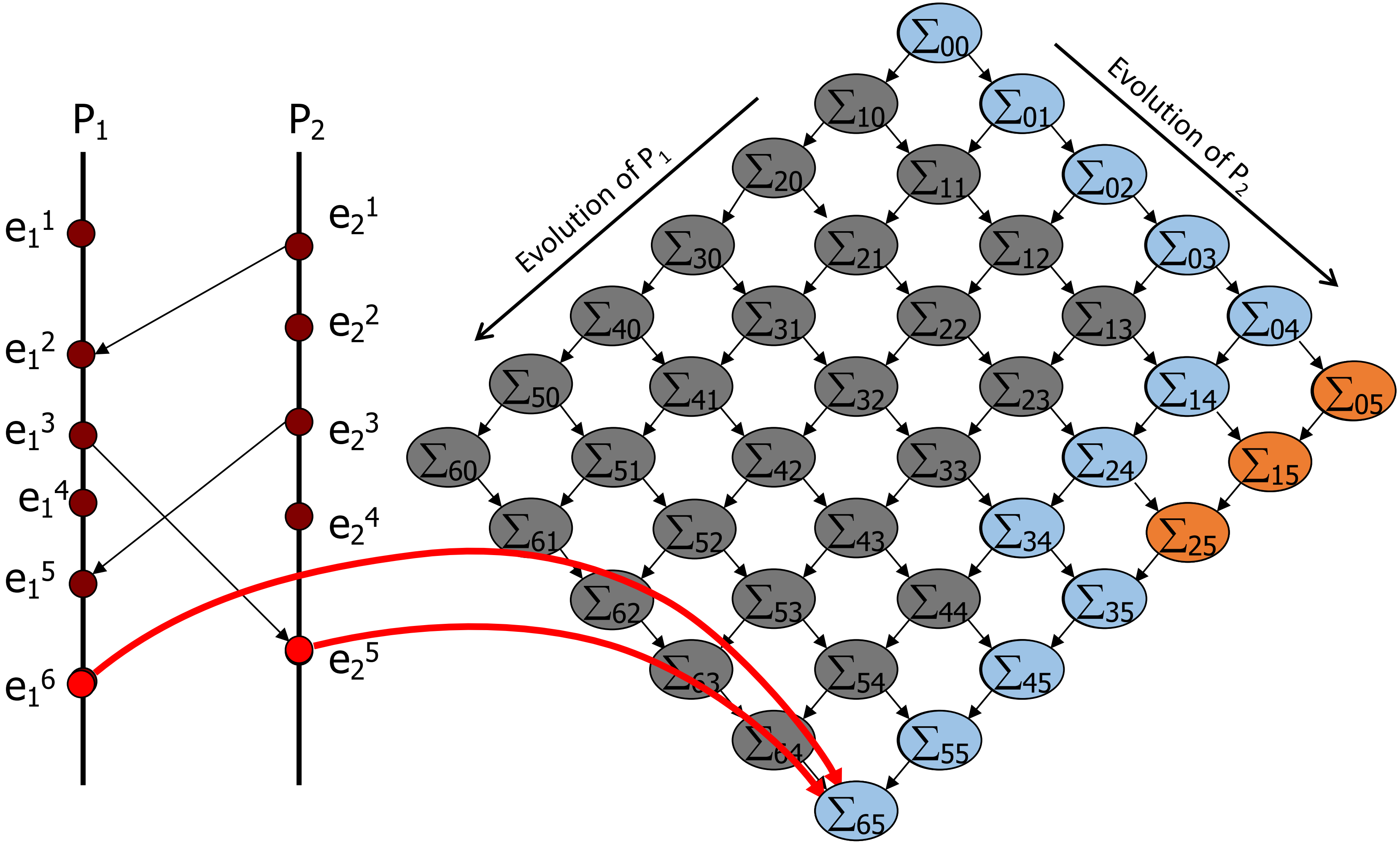
P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
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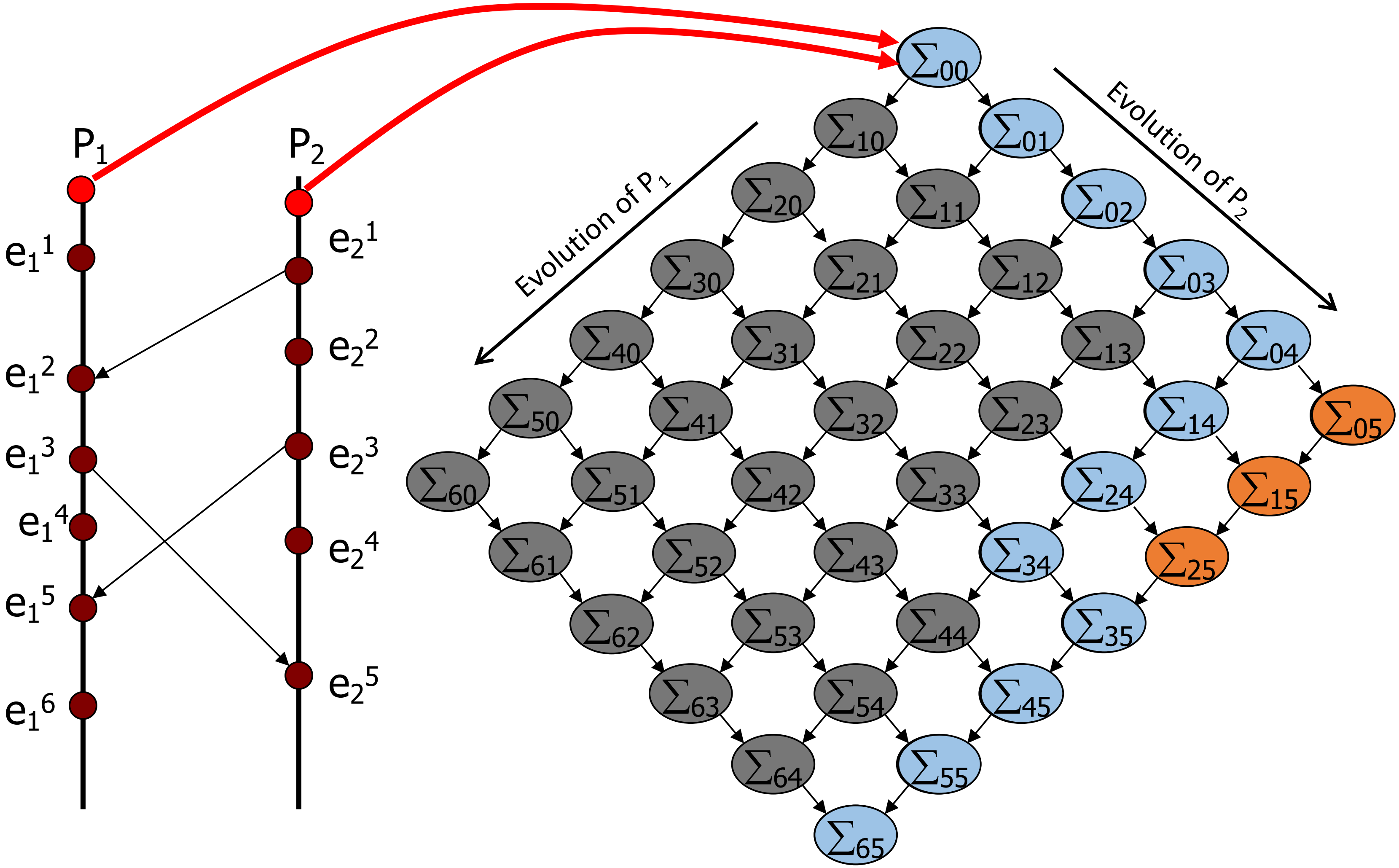
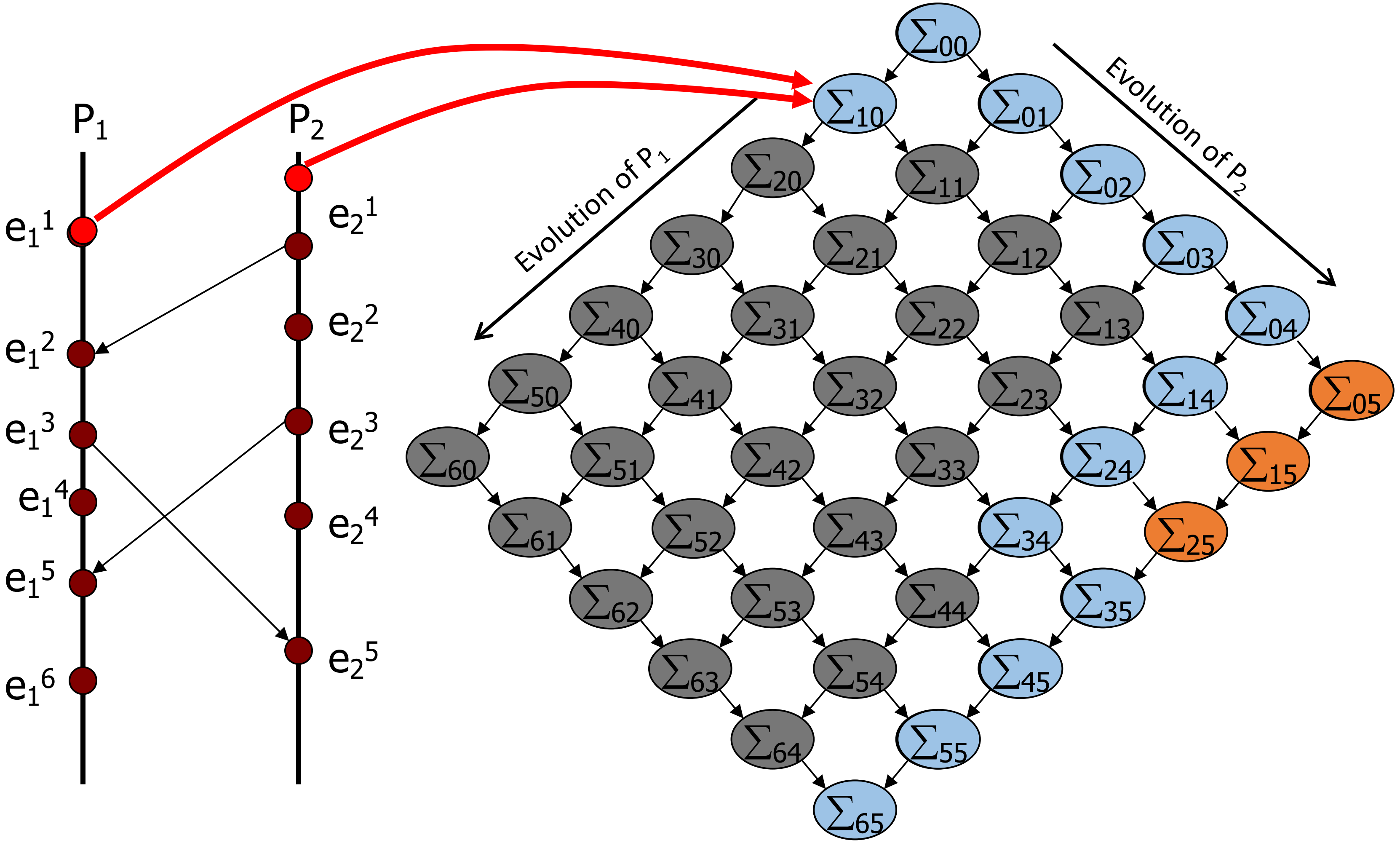
State explosion in concurrent programs



State explosion in concurrent programs



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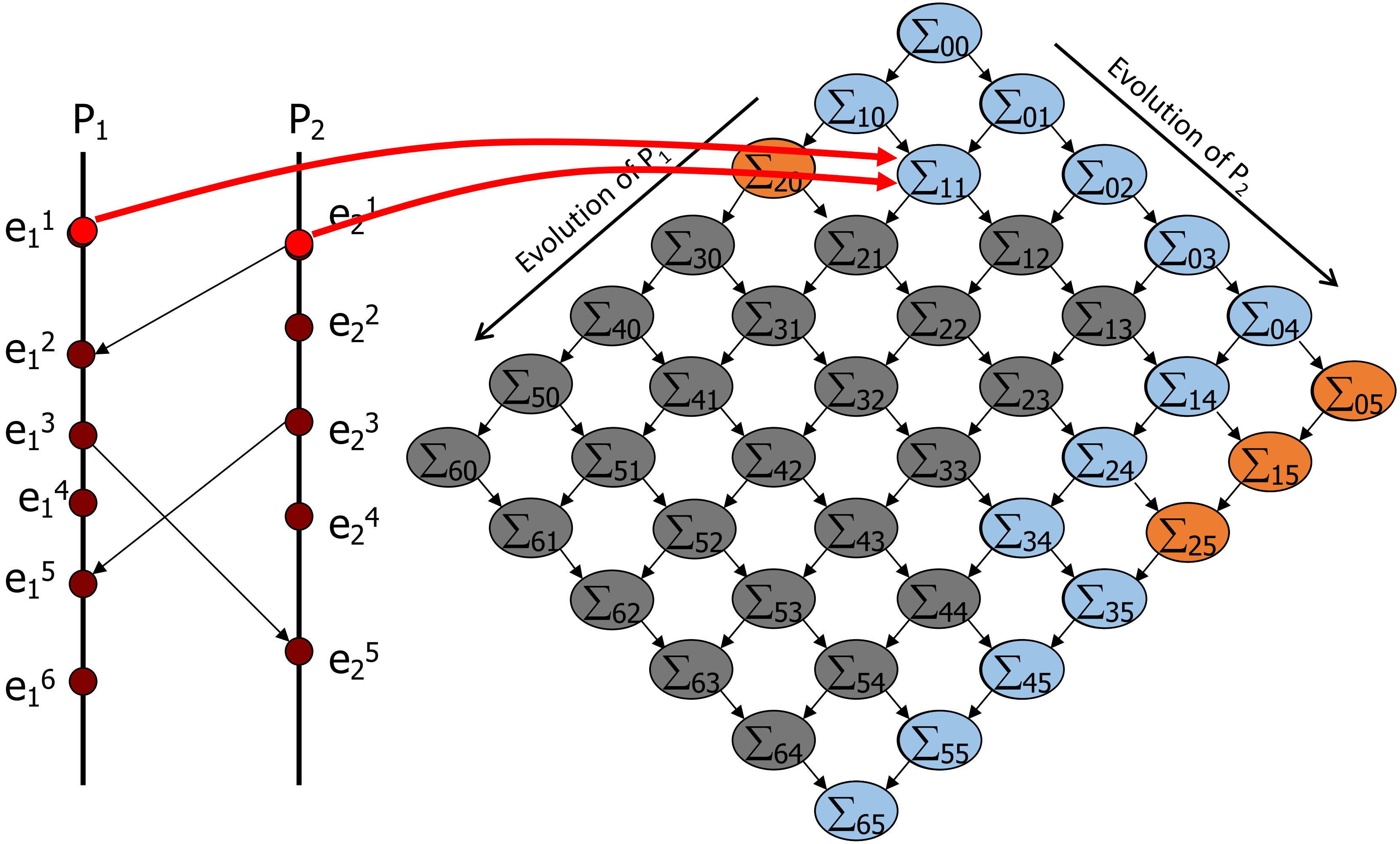

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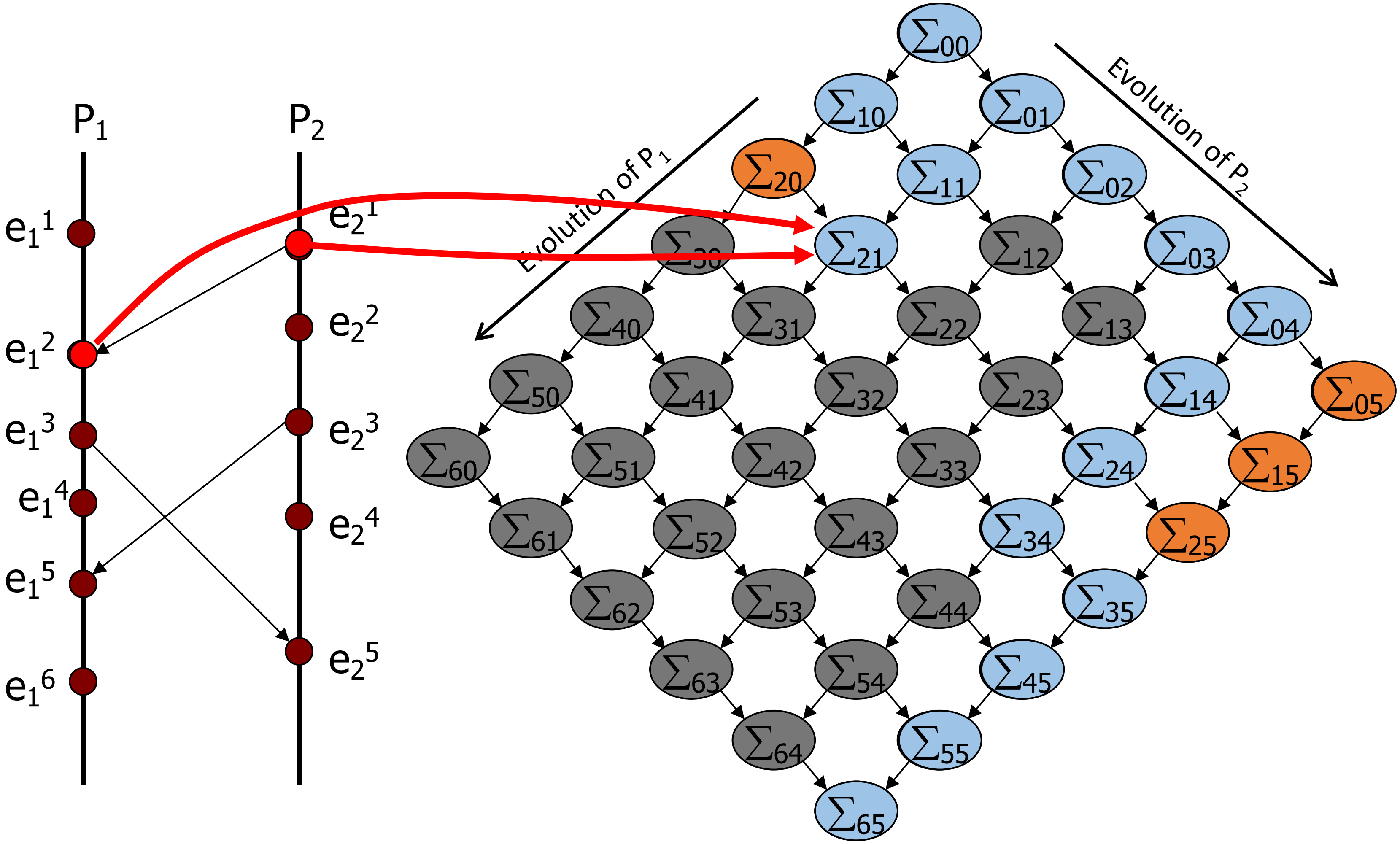
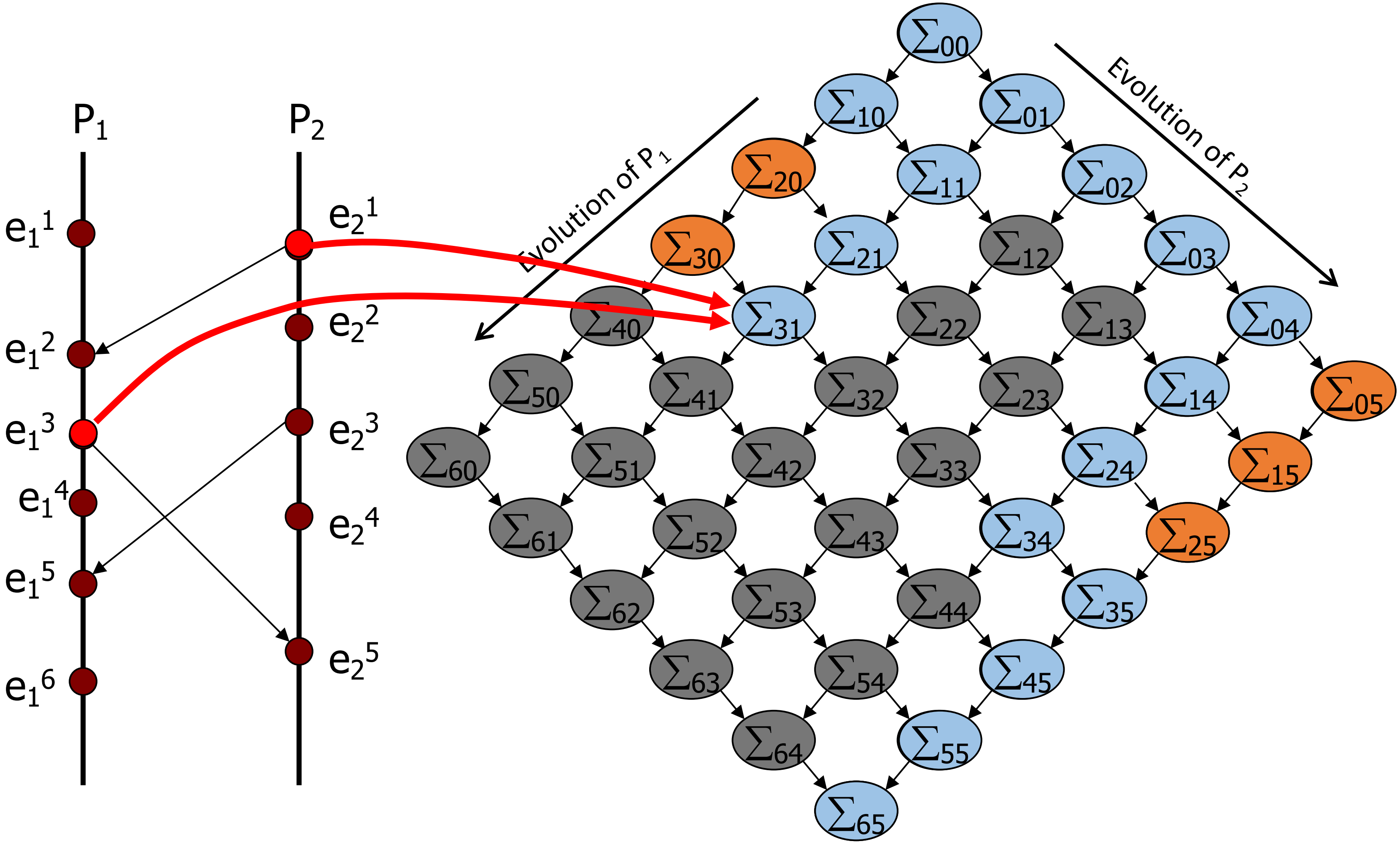


State explosion in concurrent programs



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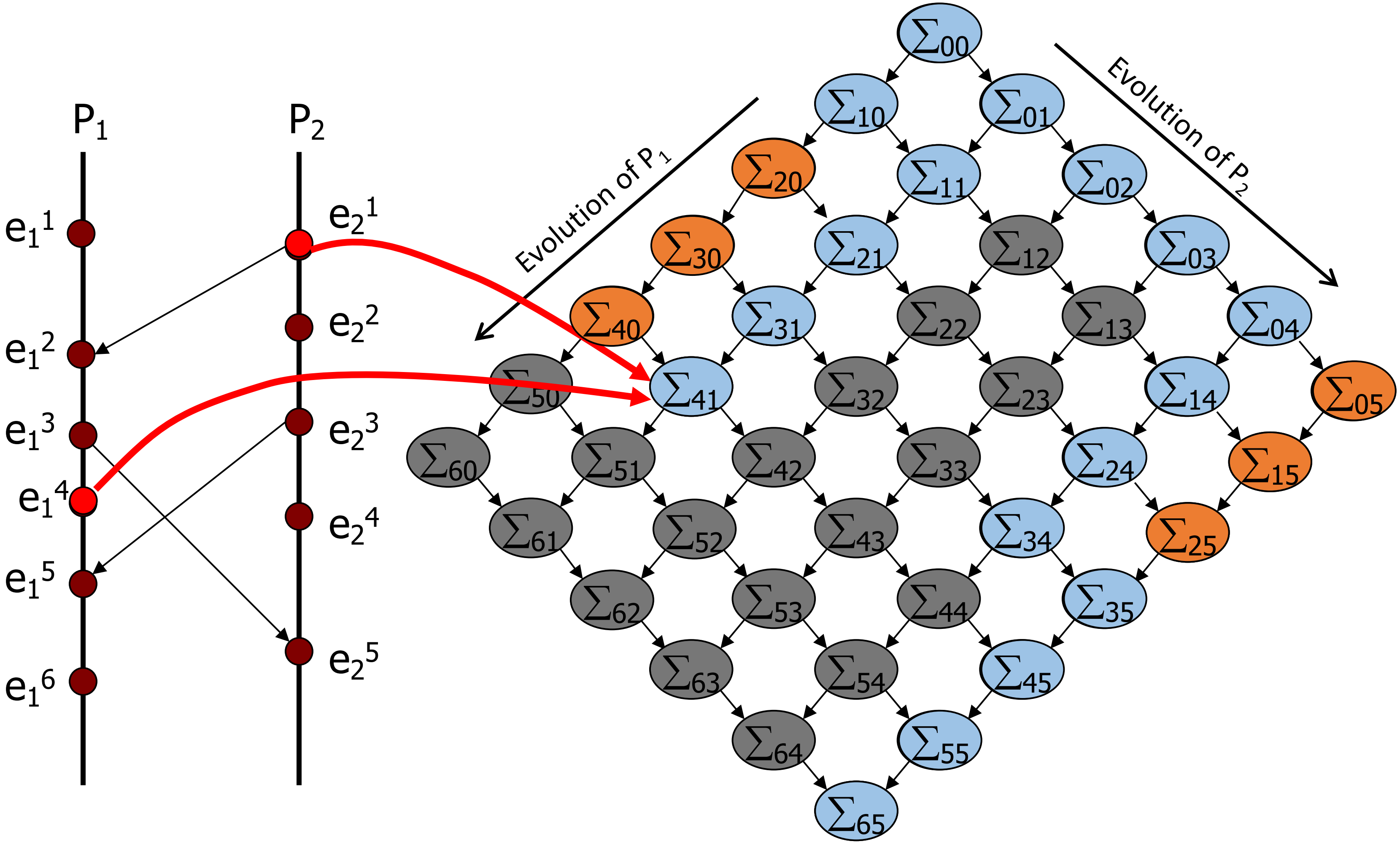

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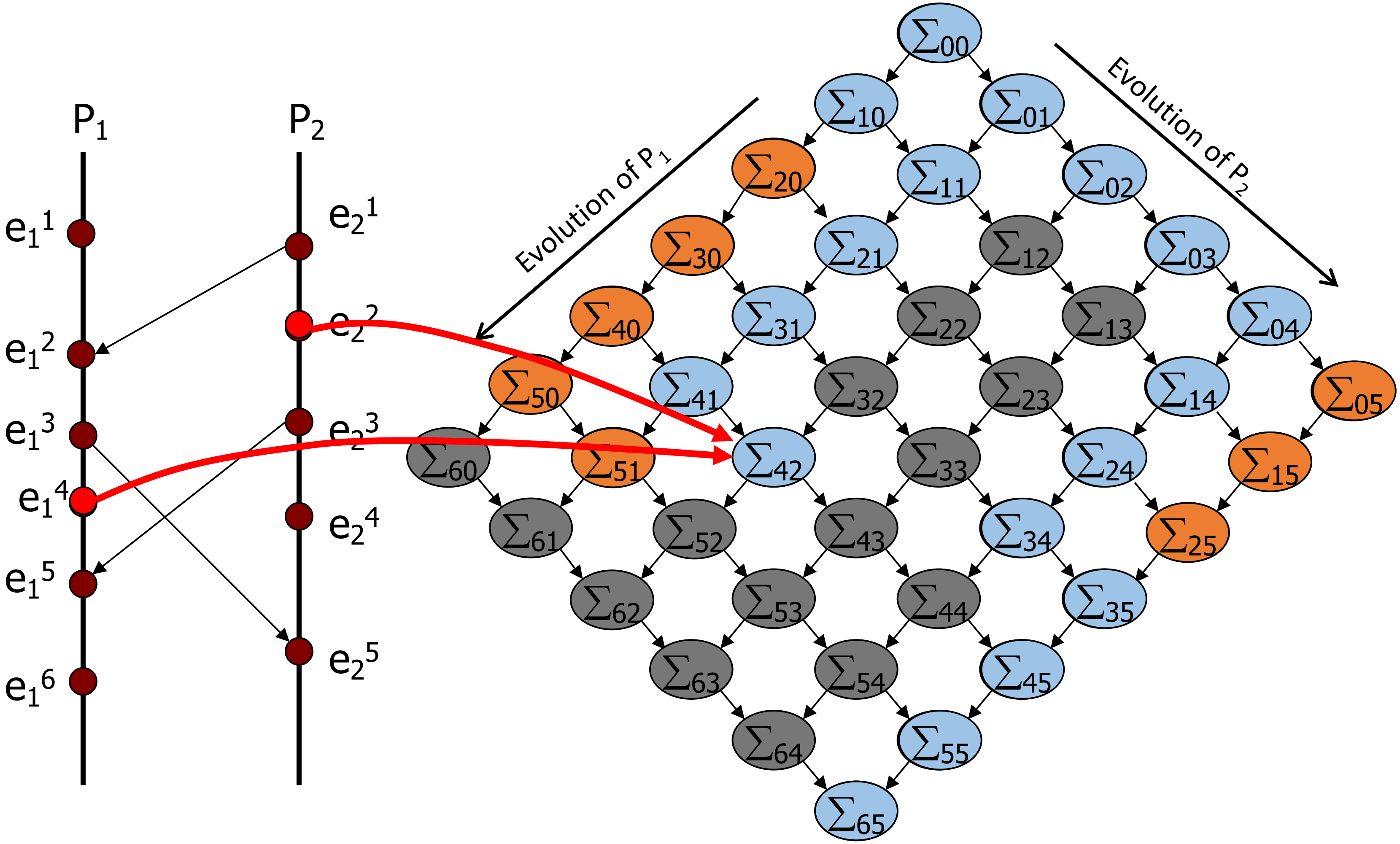

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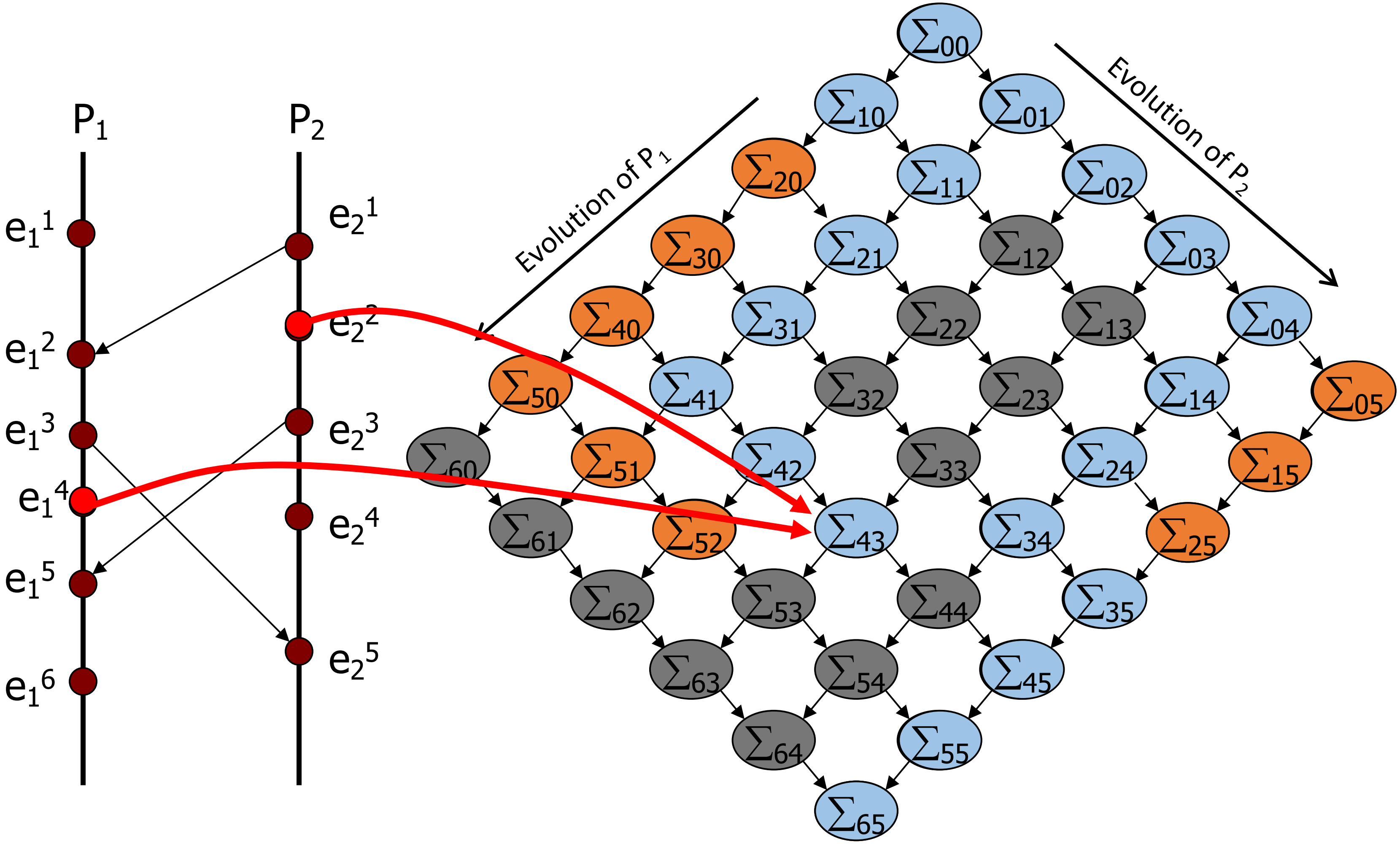

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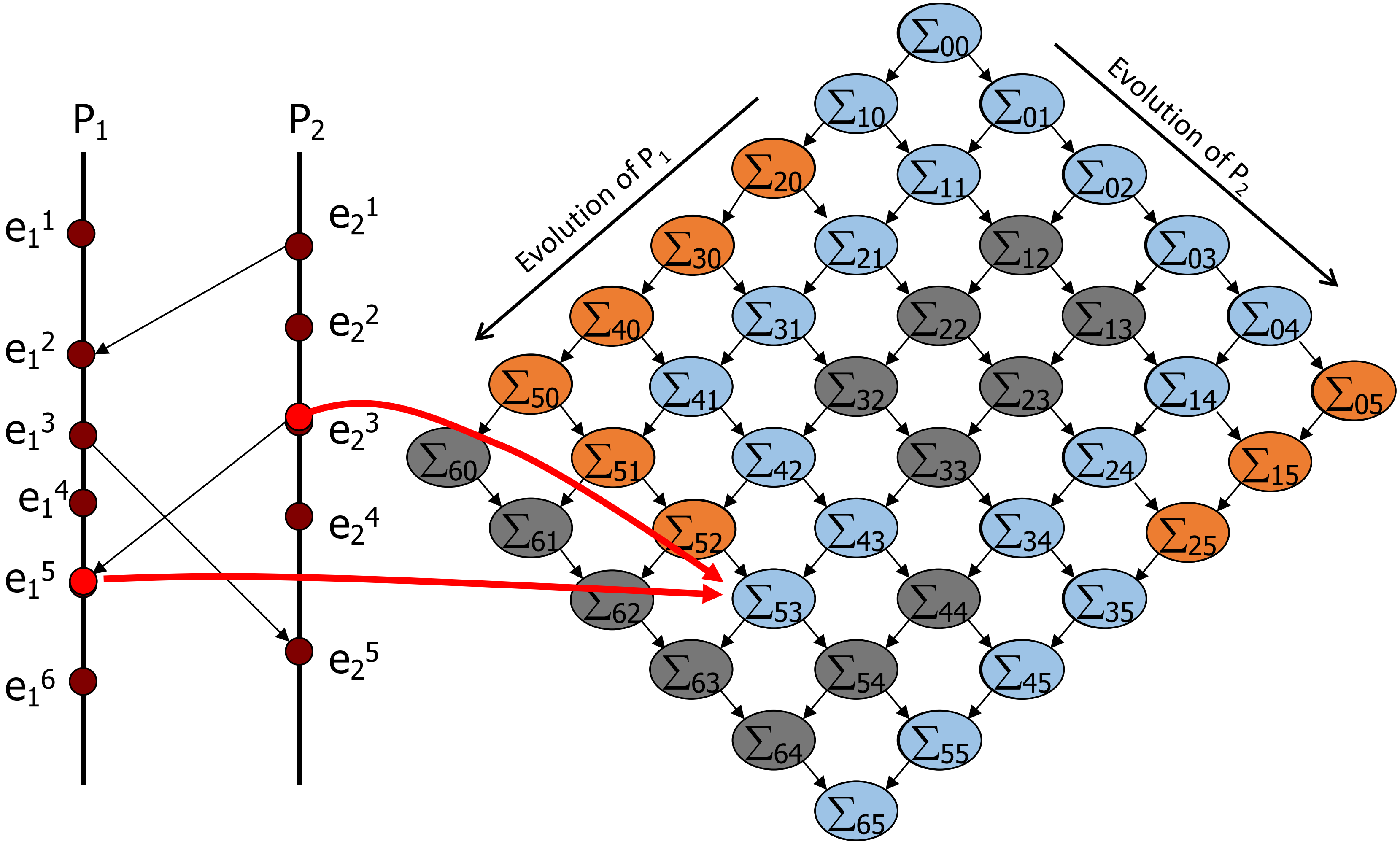

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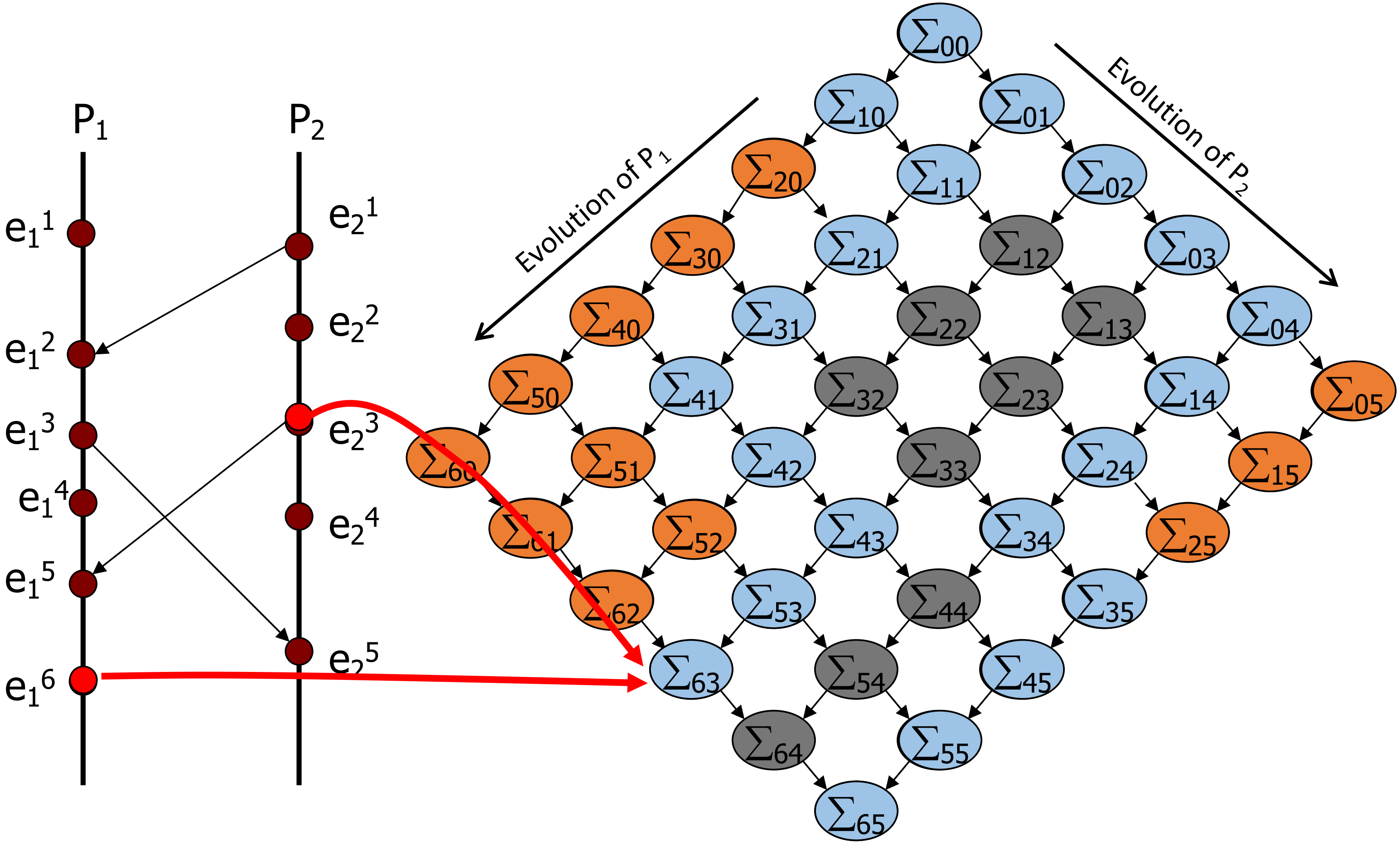

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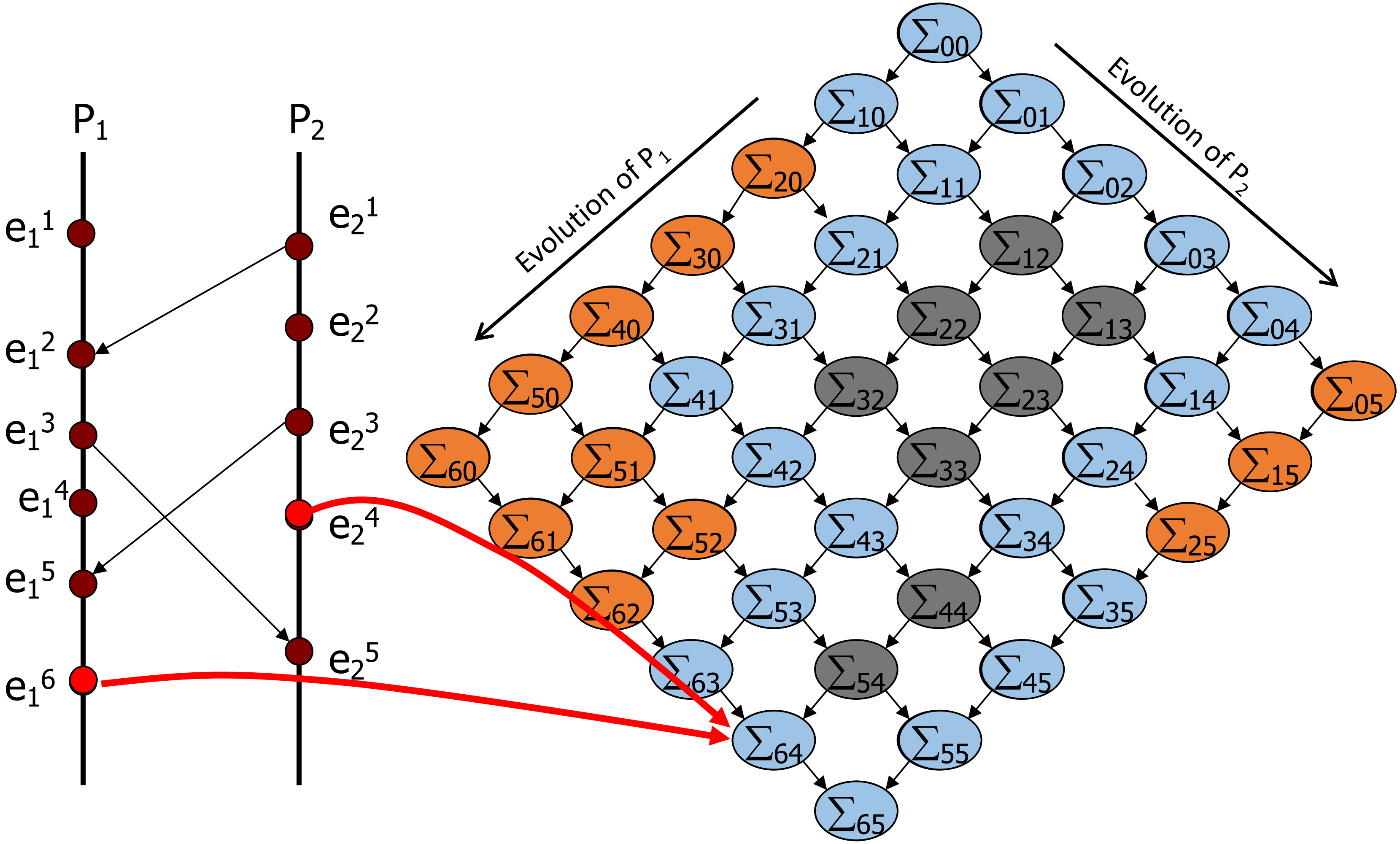

P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
Σ_{40} Σ_{31} Σ_{22} Σ_{13} Σ_{04}
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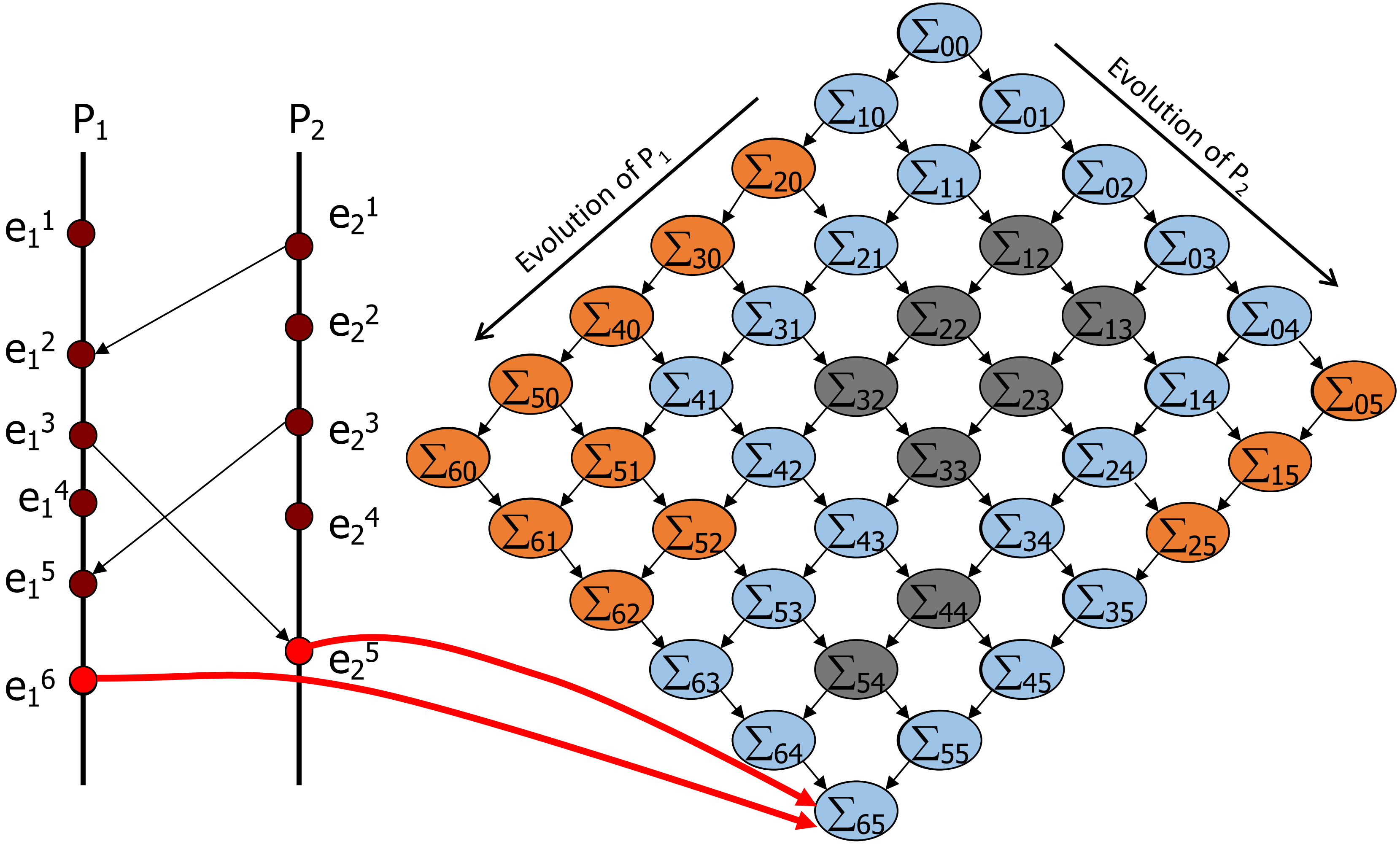
Σ_{64} Σ_{55}
Σ_{65}

State explosion in concurrent programs


P_1
P_2
e_1^1
e_1^2
e_1^3
e_1^4
e_1^5
e_1^6
e_2^1
e_2^2
e_2^3
e_2^4
e_2^5
Evolution of P_1
Evolution of P_2
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Σ_{20} Σ_{11} Σ_{02}
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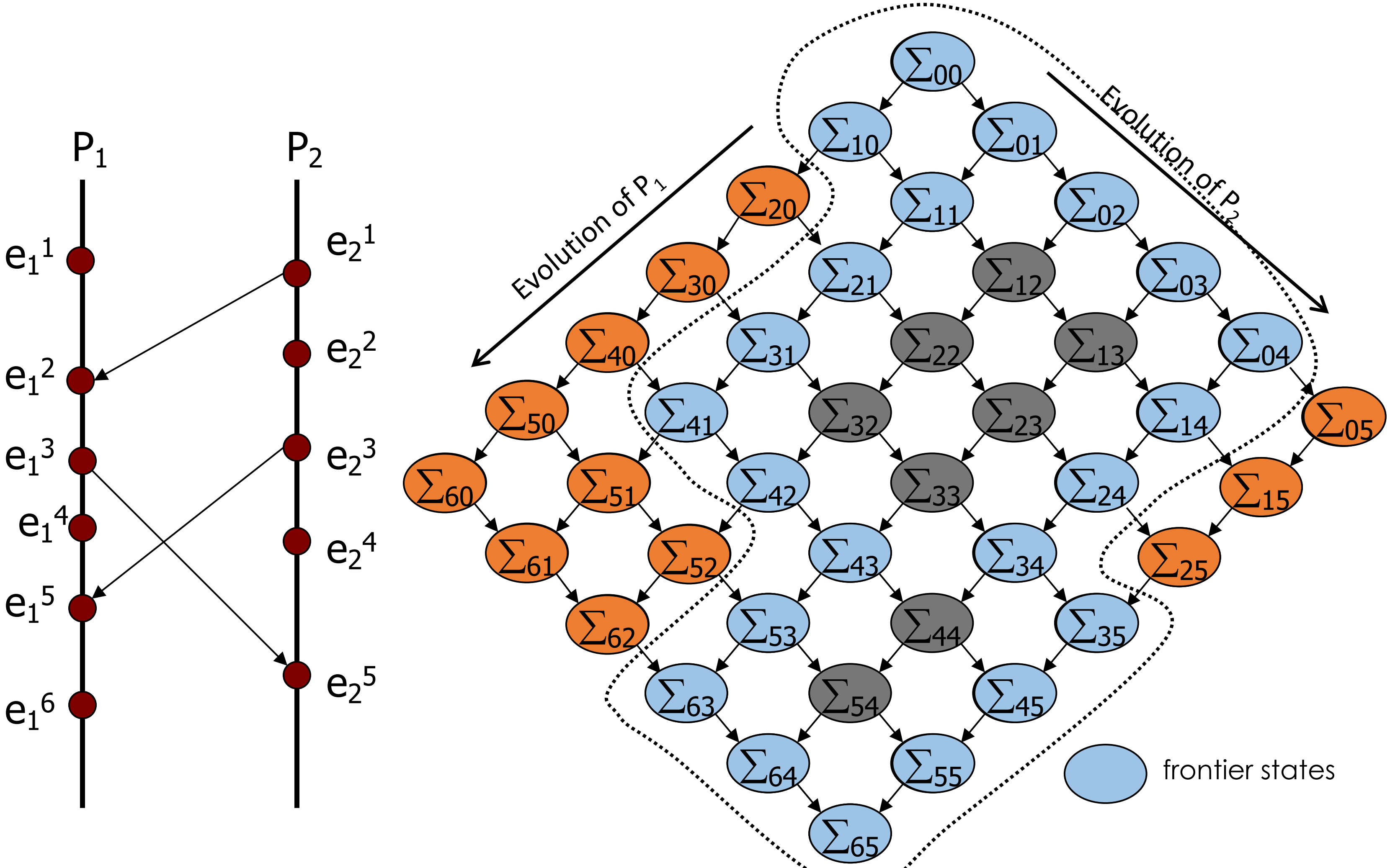
Σ_{65}

State explosion in concurrent programs



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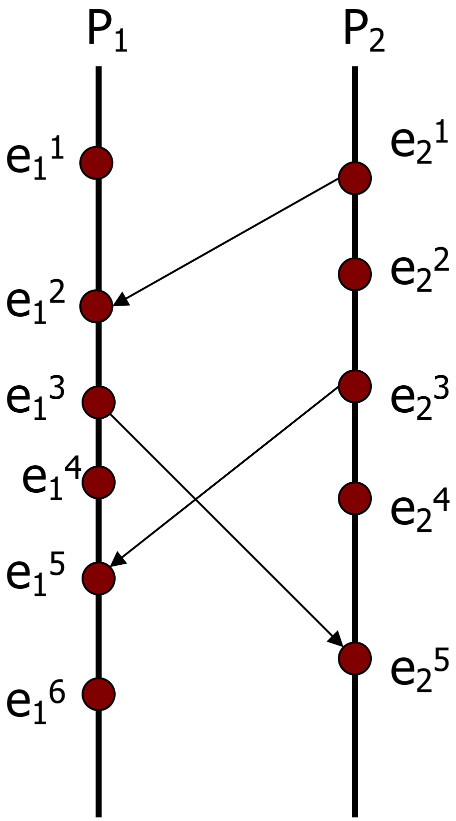
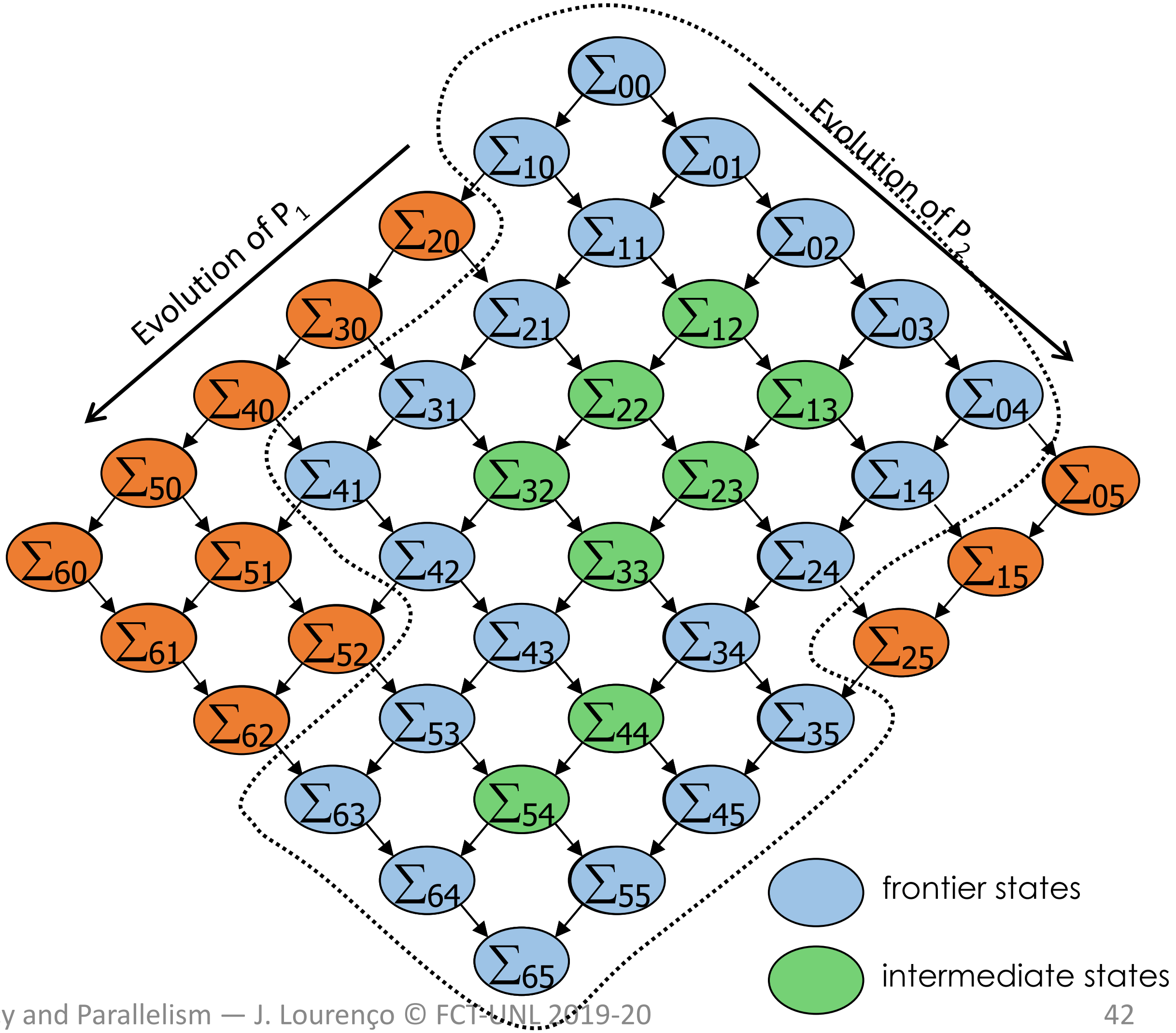
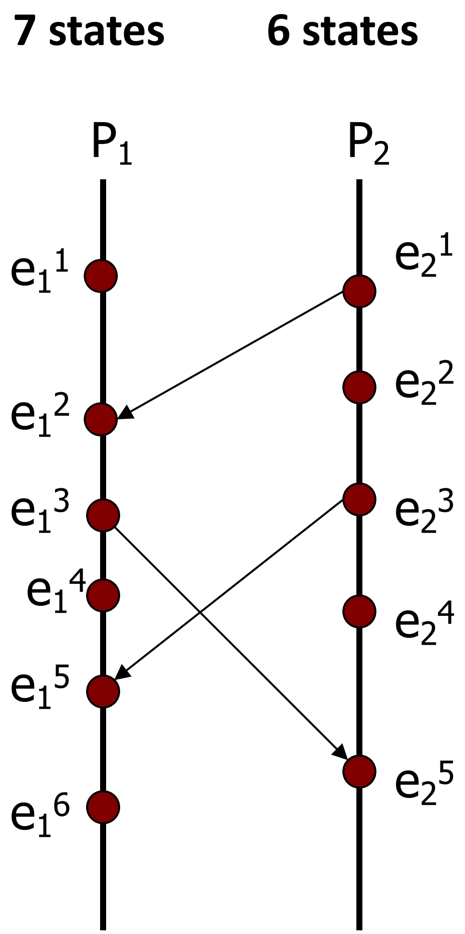
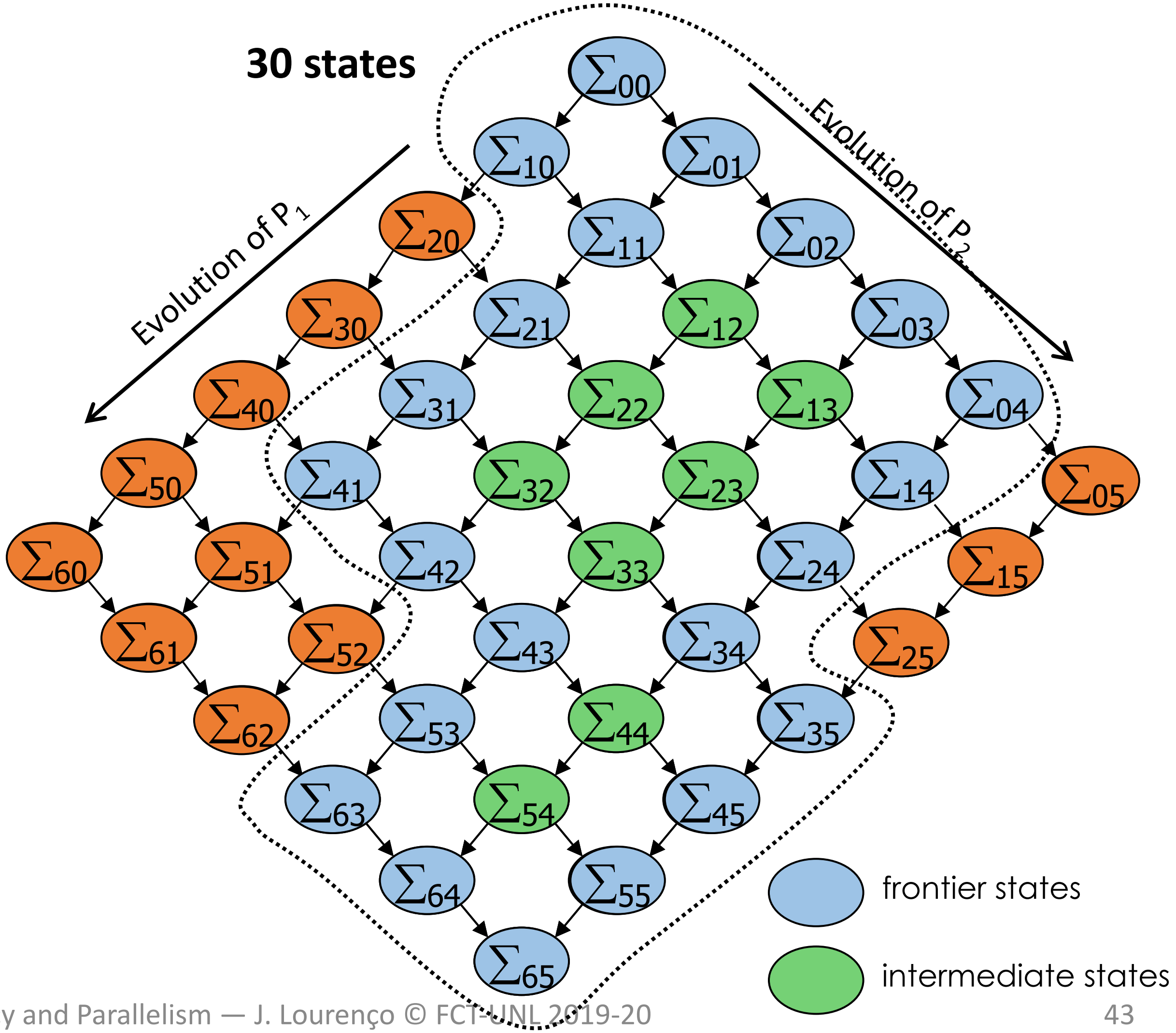




State explosion in concurrent programs




30 states
Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
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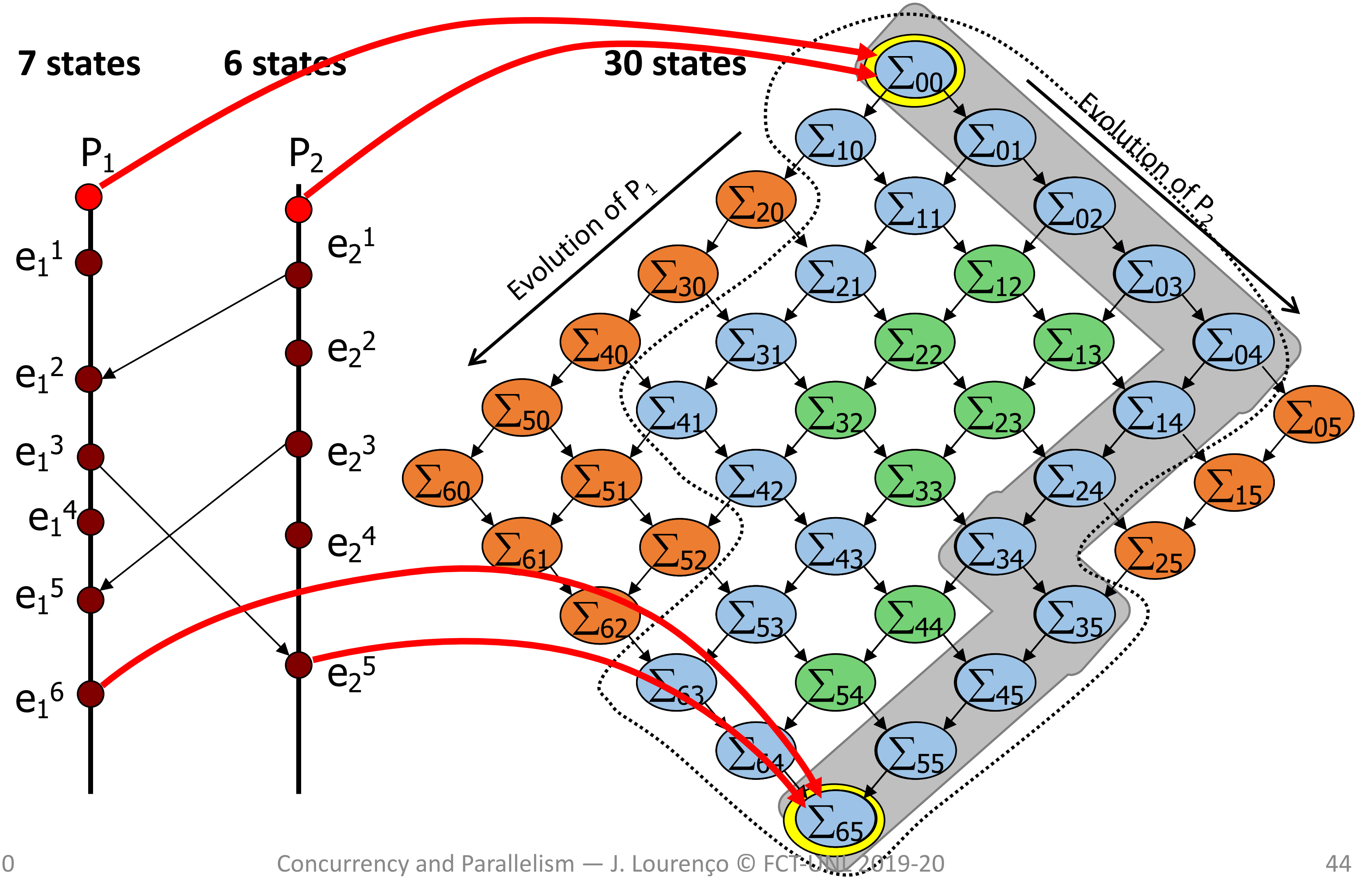
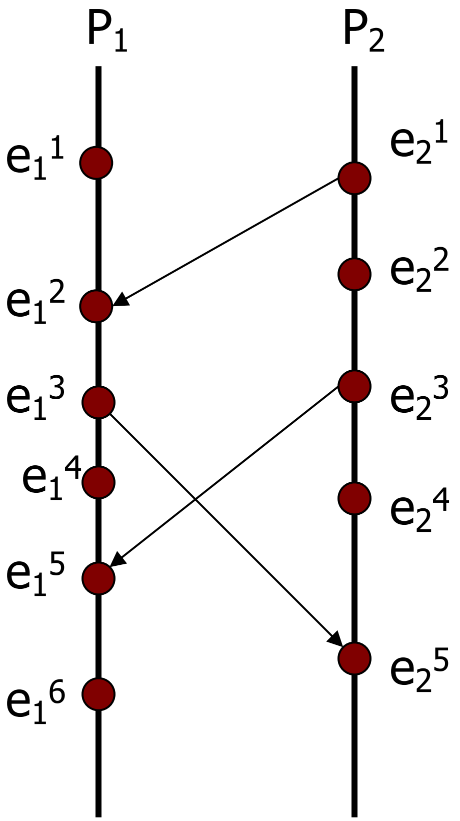
Σ_{62} Σ_{53} Σ_{44} Σ_{35}
Σ_{63} Σ_{54} Σ_{45}
Σ_{64} Σ_{55}
Σ_{65}
frontier states
intermediate states

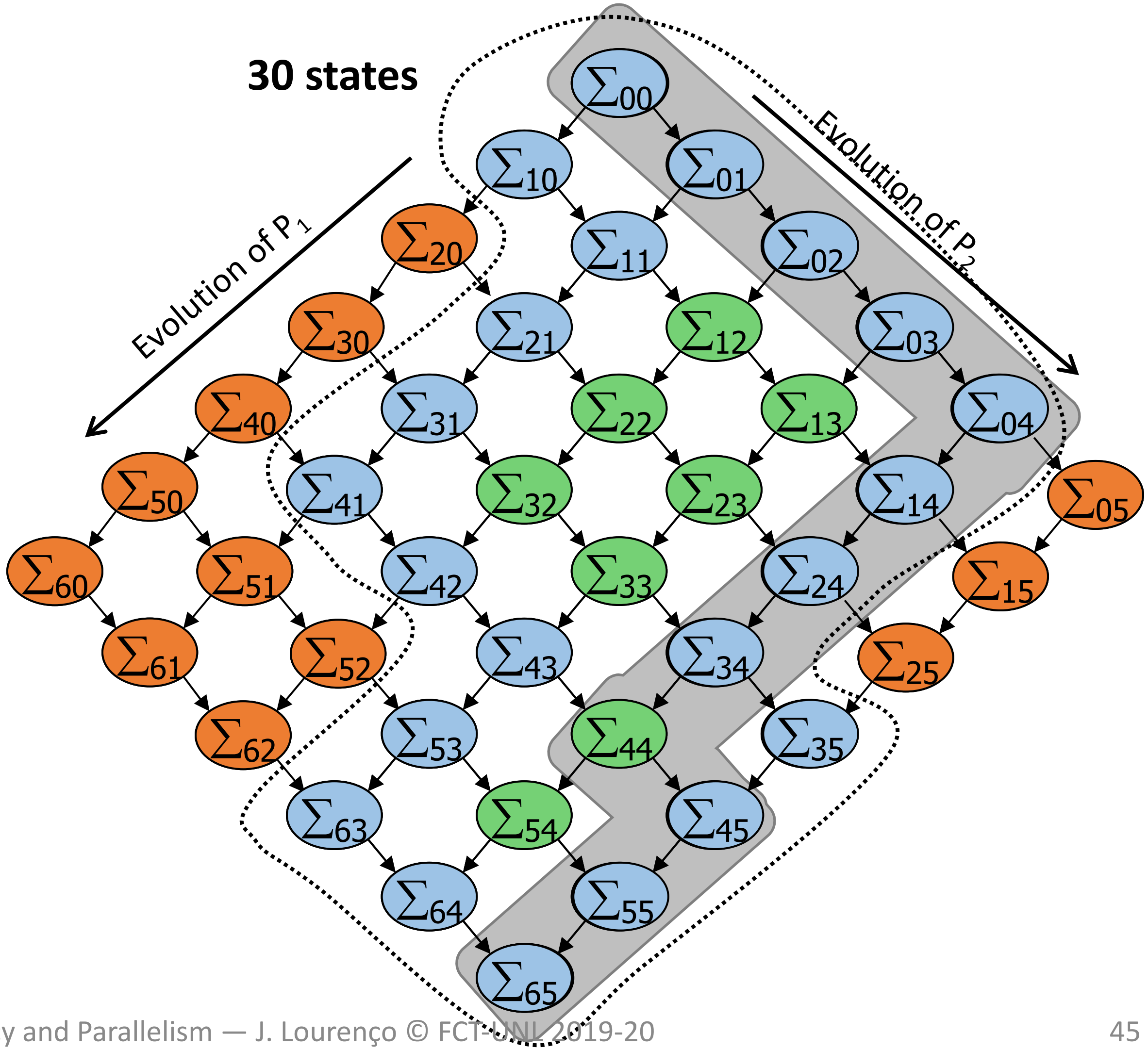
Consistent run: valid path Σ_{00} to Σ_{65}



Consistent run

7 states **6 states** **30 states**

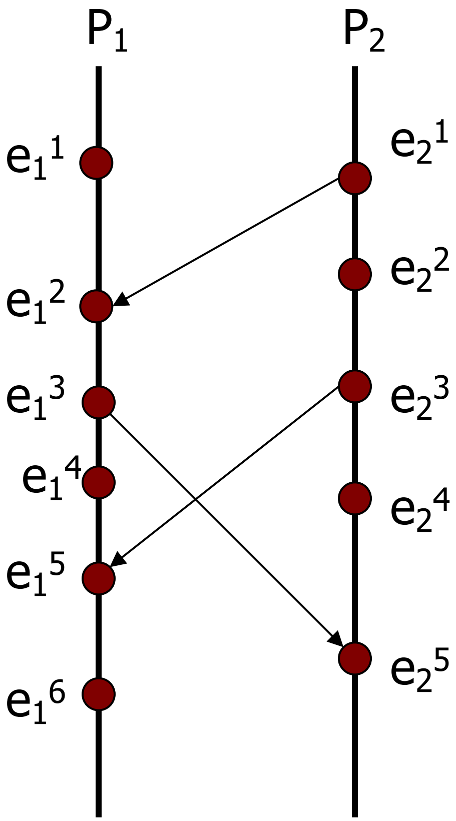


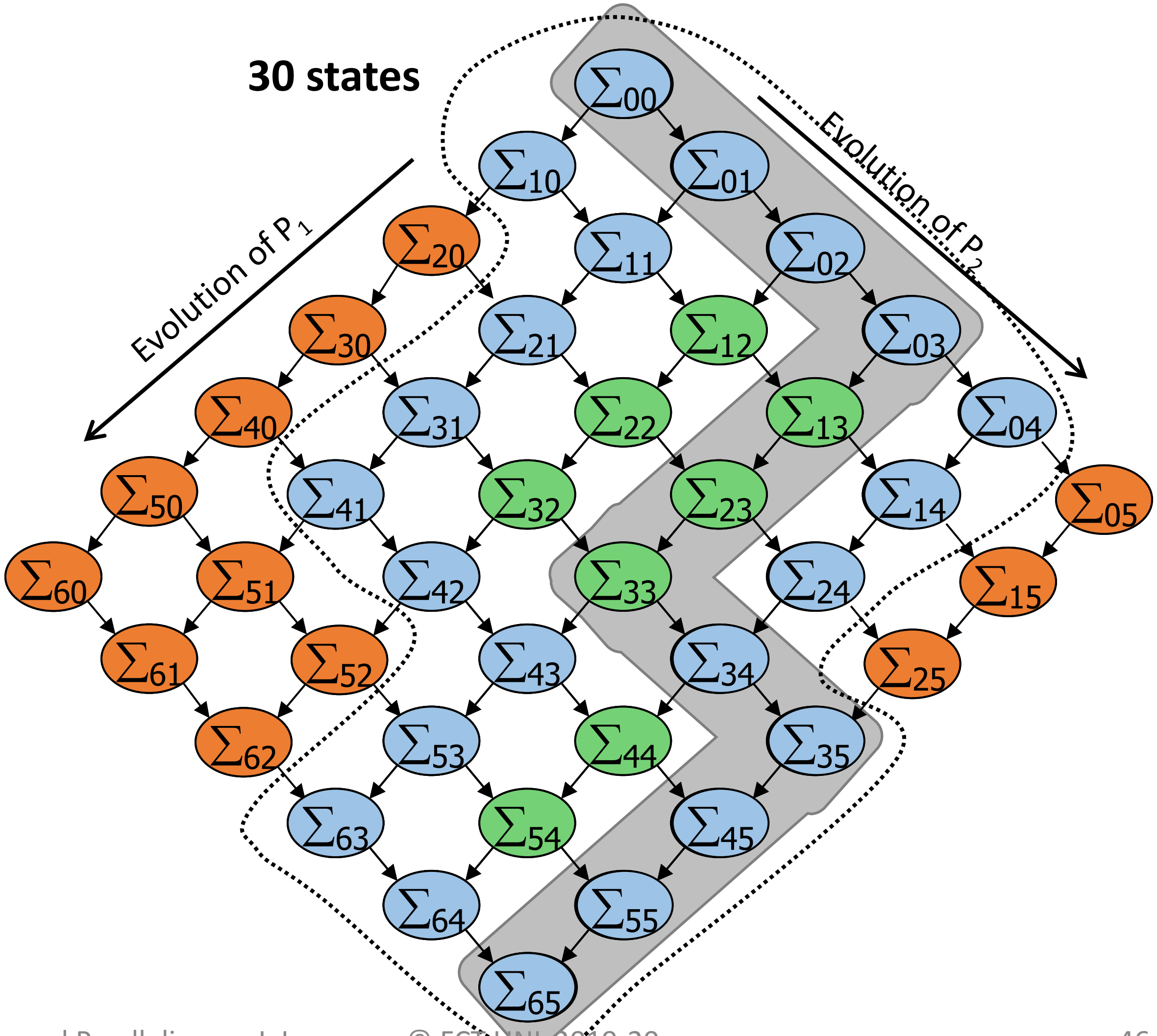


Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
Σ_{40} Σ_{31} Σ_{22} Σ_{13} Σ_{04}
Σ_{50} Σ_{41} Σ_{32} Σ_{23} Σ_{14} Σ_{05}
Σ_{60} Σ_{51} Σ_{42} Σ_{33} Σ_{24} Σ_{15}
Σ_{61} Σ_{52} Σ_{43} Σ_{34} Σ_{25}
Σ_{62} Σ_{53} Σ_{44} Σ_{35}
Σ_{63} Σ_{54} Σ_{45}
Σ_{64} Σ_{55}
Σ_{65}

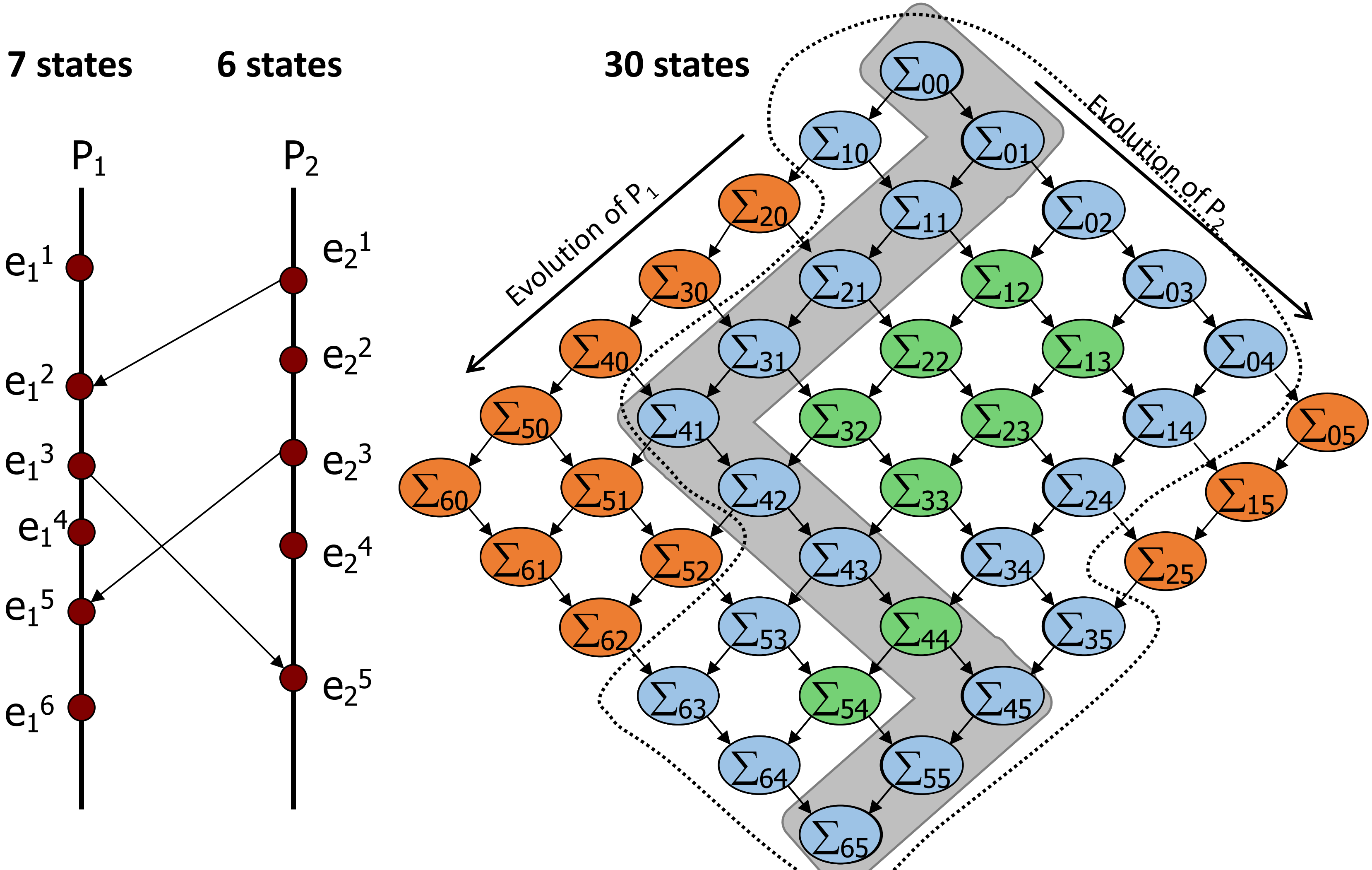
Consistent run

7 states **6 states** **30 states**



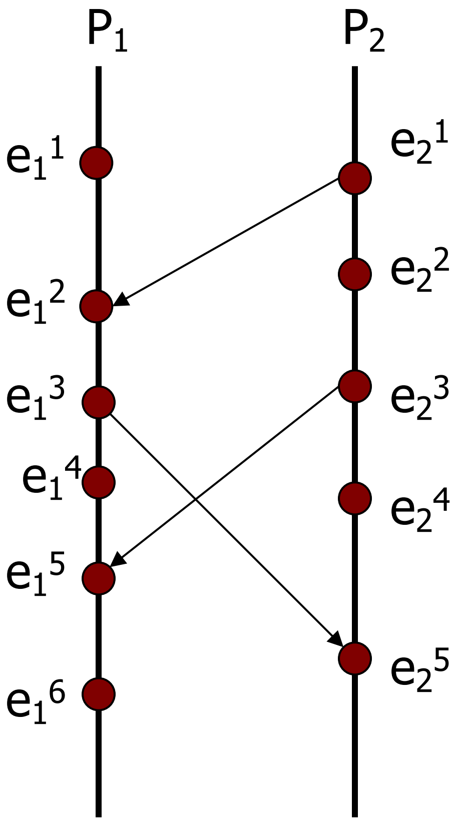


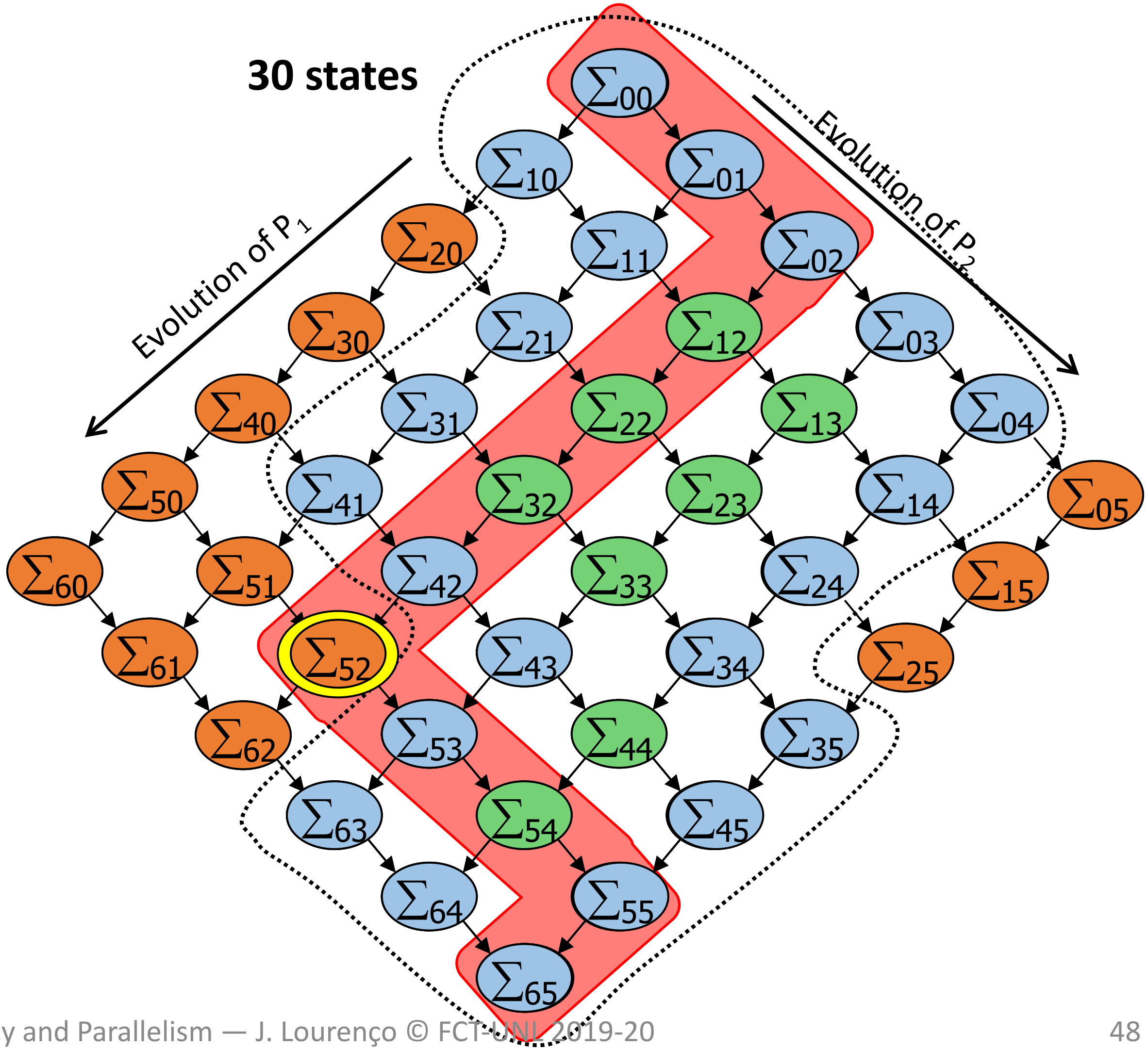
Consistent run



Inconsistent run – program error

7 states **6 states** **30 states**





Evolution of P_1
Evolution of P_2
Σ_{00}
Σ_{10} Σ_{01}
Σ_{20} Σ_{11} Σ_{02}
Σ_{30} Σ_{21} Σ_{12} Σ_{03}
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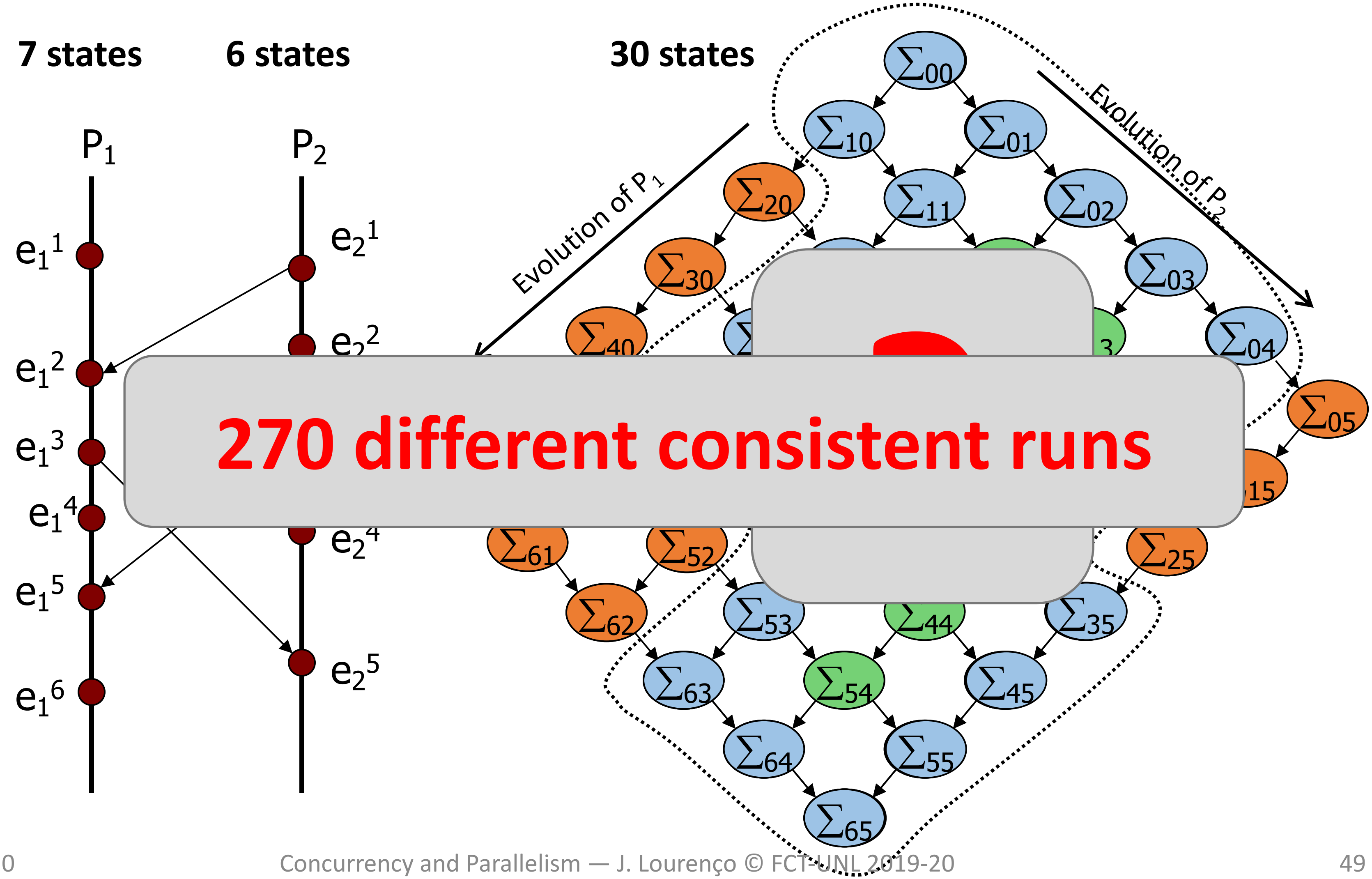
Σ_{63} Σ_{54} Σ_{45}
Σ_{64} Σ_{55}
Σ_{65}

Consistent runs – How many?



270 different consistent runs

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

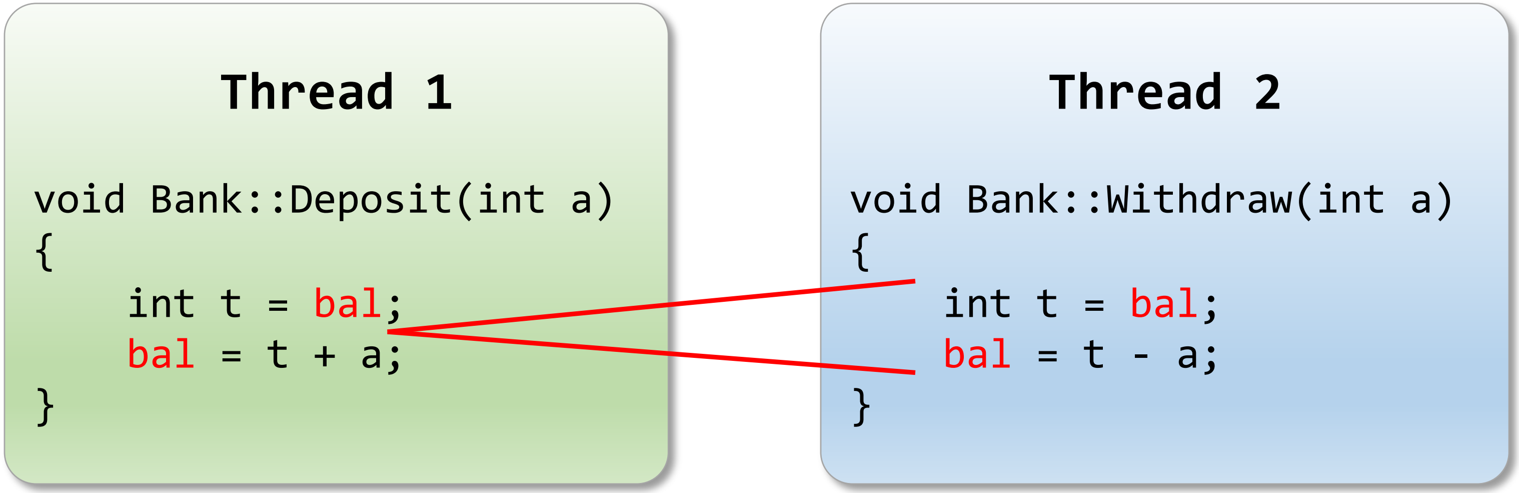
```
void Bank::Deposit(int a)
{
    int t = bal;
    bal = t + a;
}
```

Thread 2

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

Data Race

- 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;
}
```

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

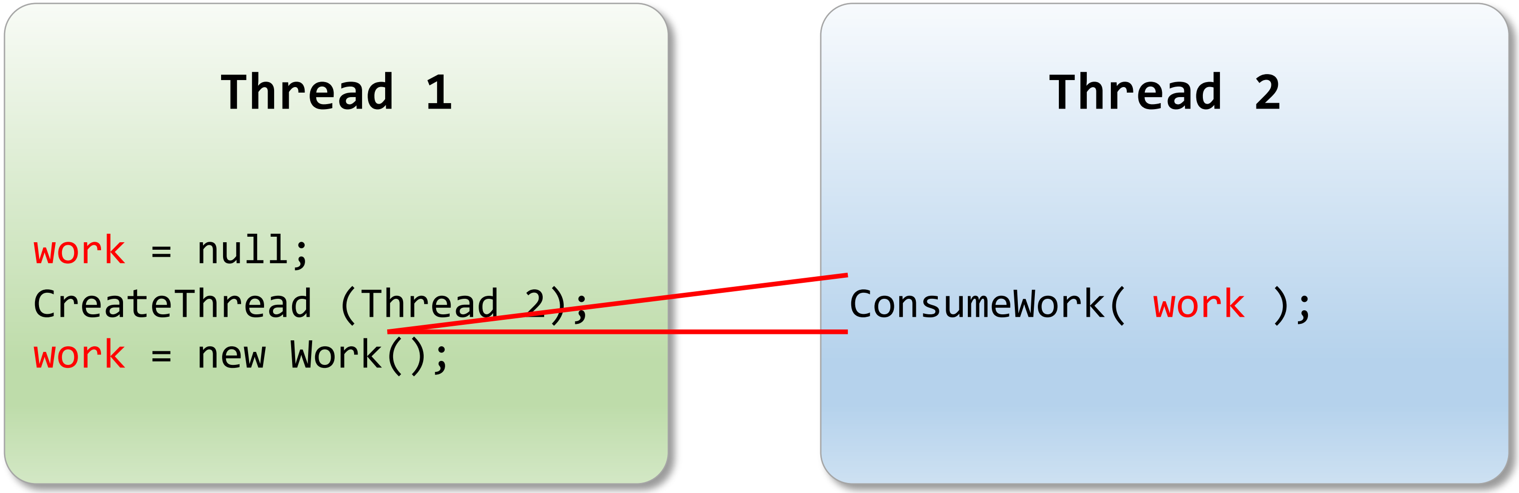
```
work = null;
CreateThread (Thread 2);
work = new Work();
```

Thread 2

```
ConsumeWork( work );
```

Ordering Violation

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



Thread 1

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

Thread 2

```
ConsumeWork( work );
```

'work' is not initialized yet!

Unintended Sharing

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

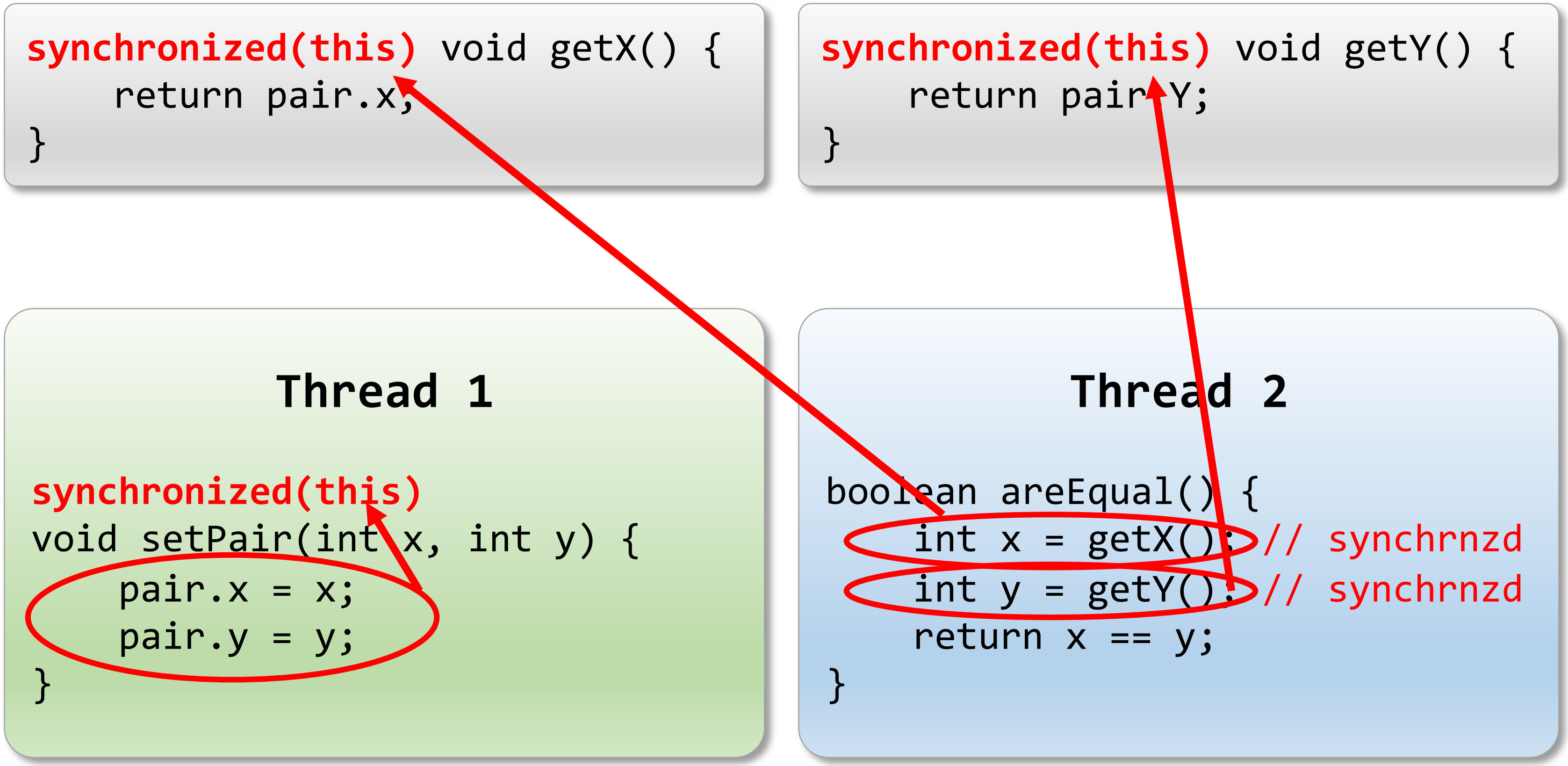
```
void work() {
   static int local = 0;
   …
   local += …
   …
}
```

```
Thread 1
…
work()
…
```

```
Thread 2
…
work()
…
```

High-Level Data Race

- Wrongly defined atomic blocks



```
synchronized(this) void getX() {
    return pair.x;
}
```

```
synchronized(this) void getY() {
    return pair.Y;
}
```

Thread 1

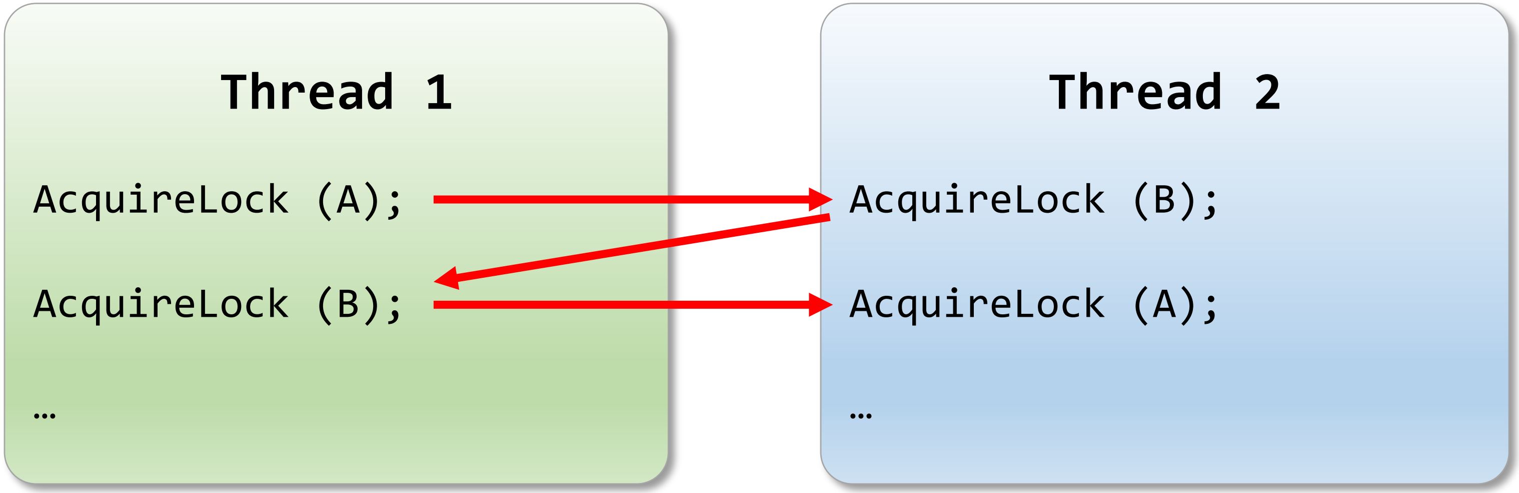
```
synchronized(this)
void setPair(int x, int y) {
    pair.x = x;
    pair.y = y;
}
```

Thread 2

```
boolean areEqual() {
    int x = getX(); // synchrnzd
    int y = getY(); // synchrnzd
    return x == y;
}
```

Deadlock

- Processes are waiting forever for each other



Thread 1

```
AcquireLock (A);

AcquireLock (B);

…
```

Thread 2

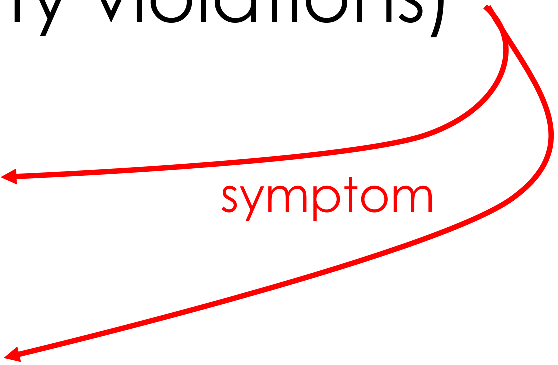
```
AcquireLock (B);

AcquireLock (A);

…
```

Common Concurrency Errors

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



Common Concurrency Errors

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

Concurrency Errors

Data Races

What is a Data Race?

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

What is a Data Race?

- Two conflicting memory accesses happening concurrently

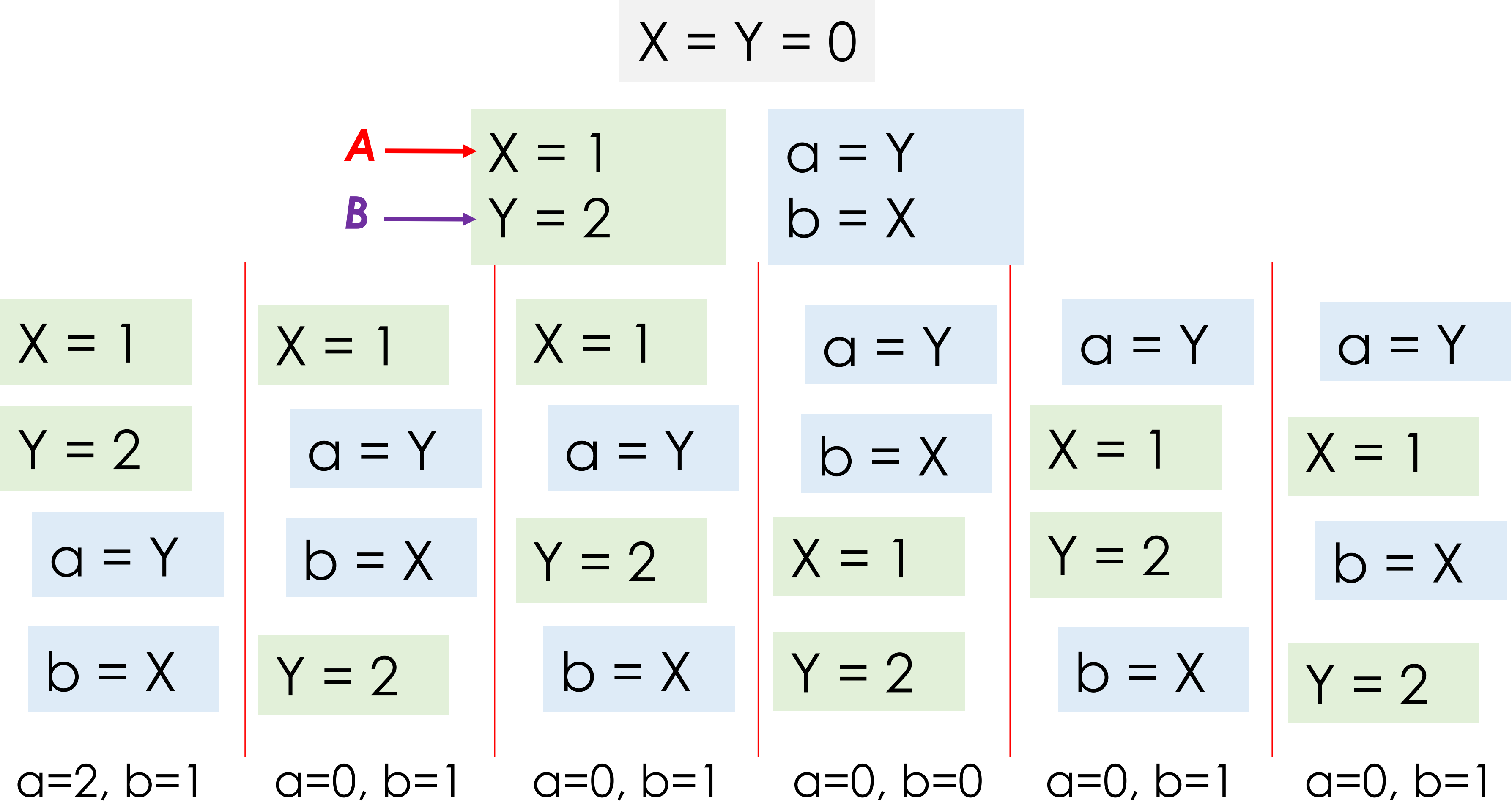
- Which means:
  - They access the same memory location
  - At least one is an update (write)

- 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



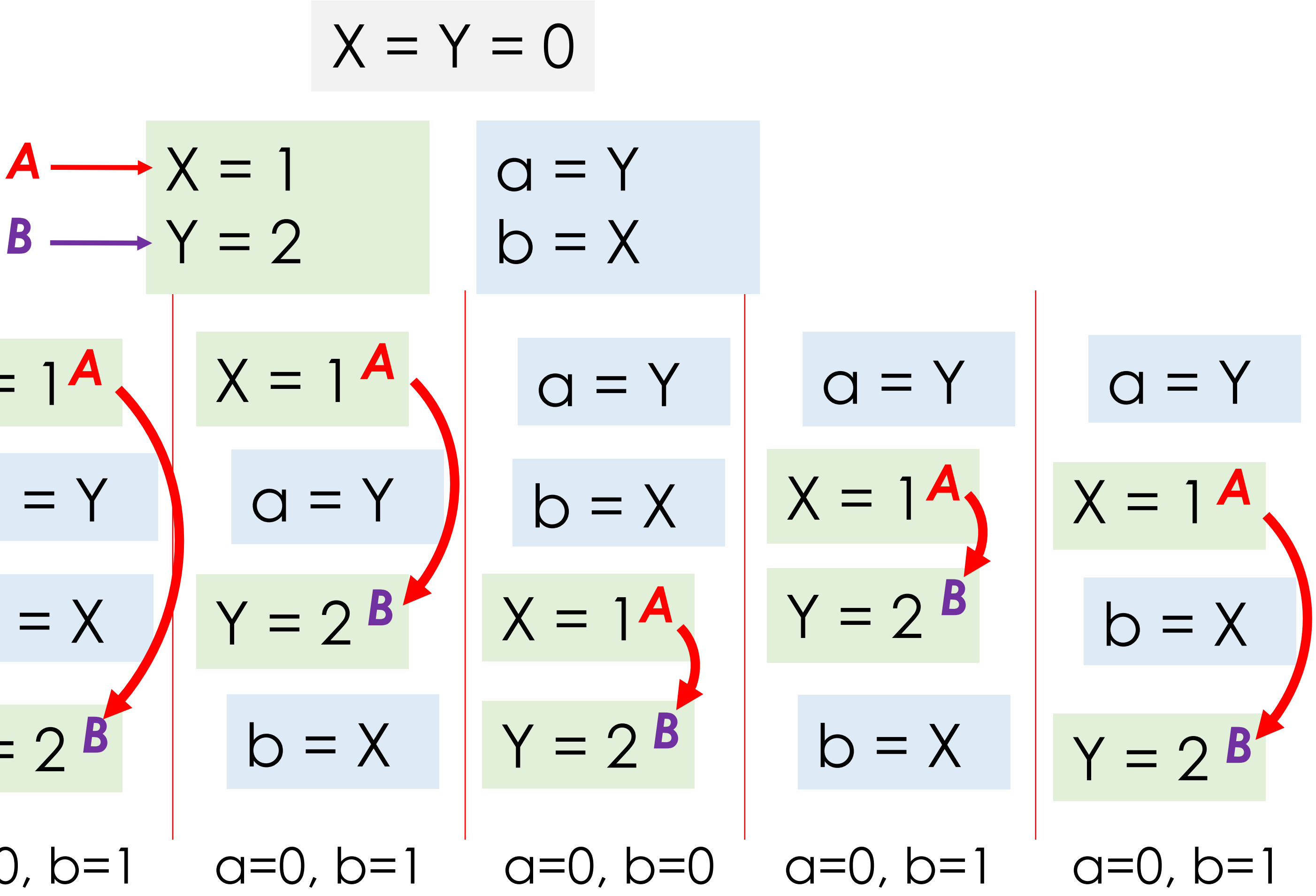
X = Y = 0

A → X = 1
B → Y = 2

a = Y
b = X

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

Assigning Semantics to Concurrent Programs



X = Y = 0

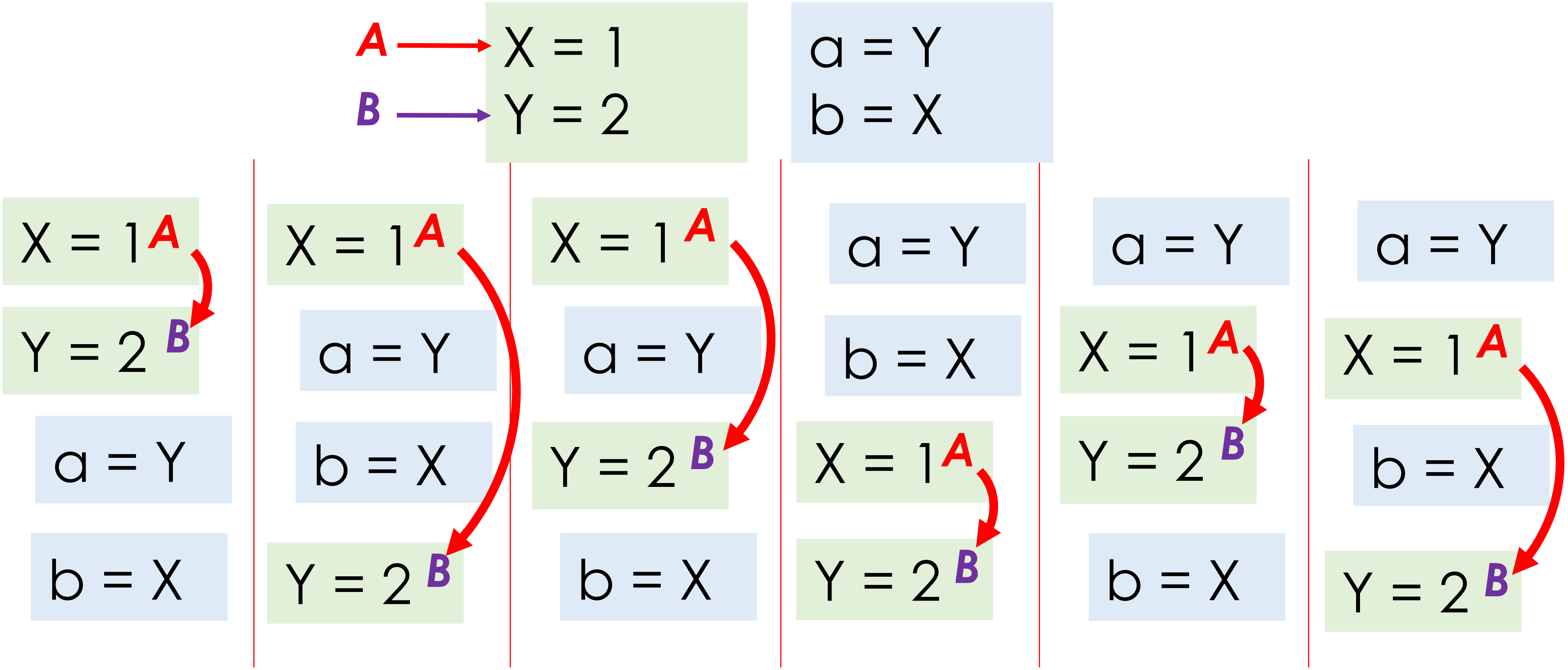
A → X = 1
B → Y = 2

a = Y
b = X

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

Assigning Semantics to Concurrent Programs

X = Y = 0



A → X = 1
B → Y = 2

a = Y
b = X

X = 1 A
Y = 2 B
a = Y
b = X

X = 1 A
a = Y
b = X
Y = 2 B

X = 1 A
a = Y
Y = 2 B
b = X

a = Y
b = X
X = 1 A
Y = 2 B

a = Y
X = 1 A
Y = 2 B
b = X

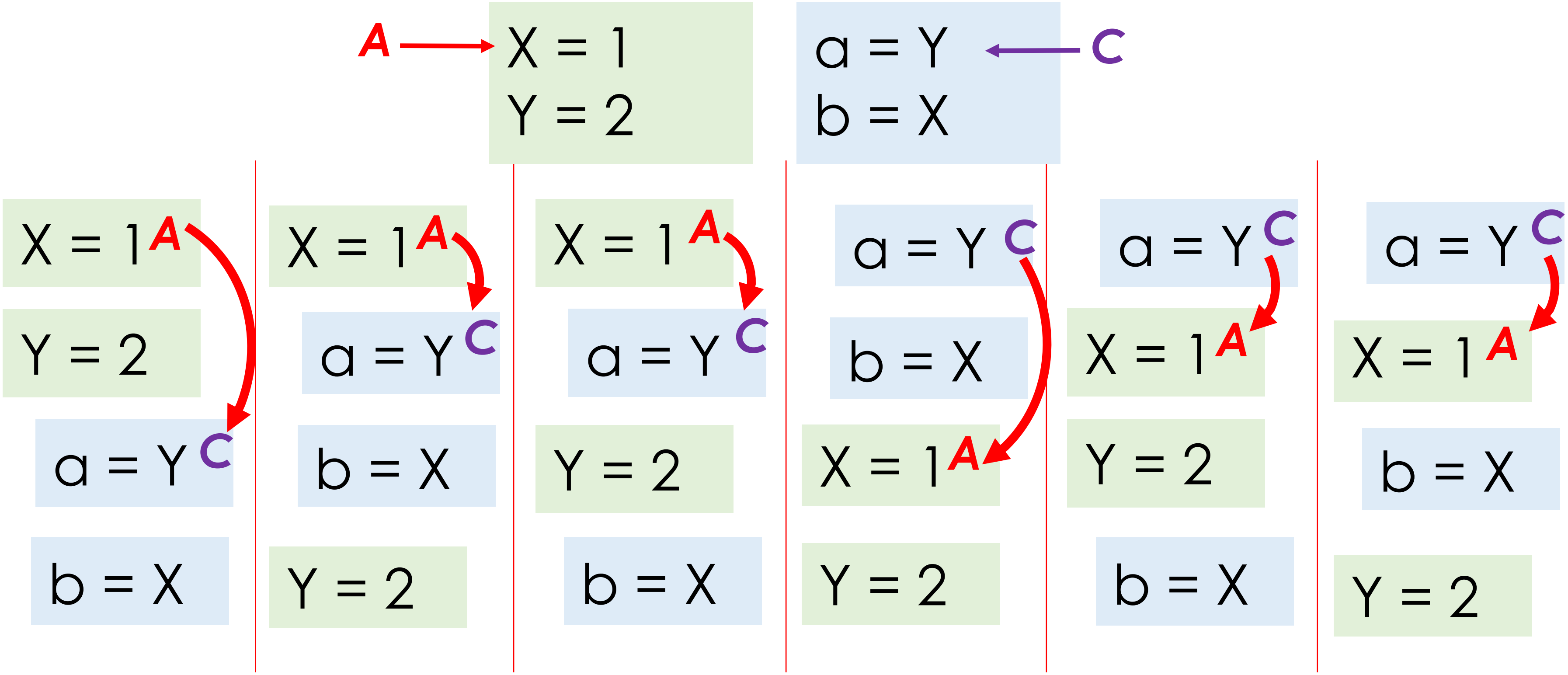
a = Y
X = 1 A
b = X
Y = 2 B

a=2, b=1	a=0, b=1	a=0, b=1	a=0, b=0	a=0, b=1	a=0, b=1

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

Assigning Semantics to Concurrent Programs

X = Y = 0



A → X = 1
Y = 2

a = Y ← C
b = X

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

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

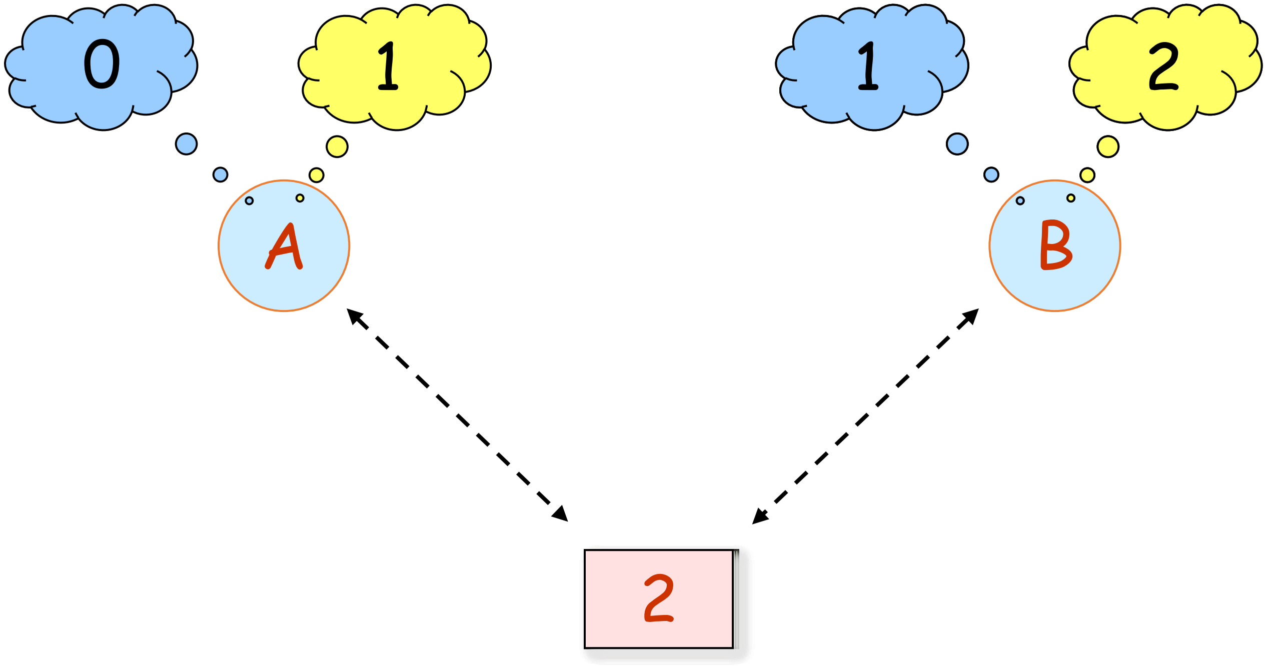
```
for (i = 0; i < 5;  i++) {
    x = x + 1
}
```

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