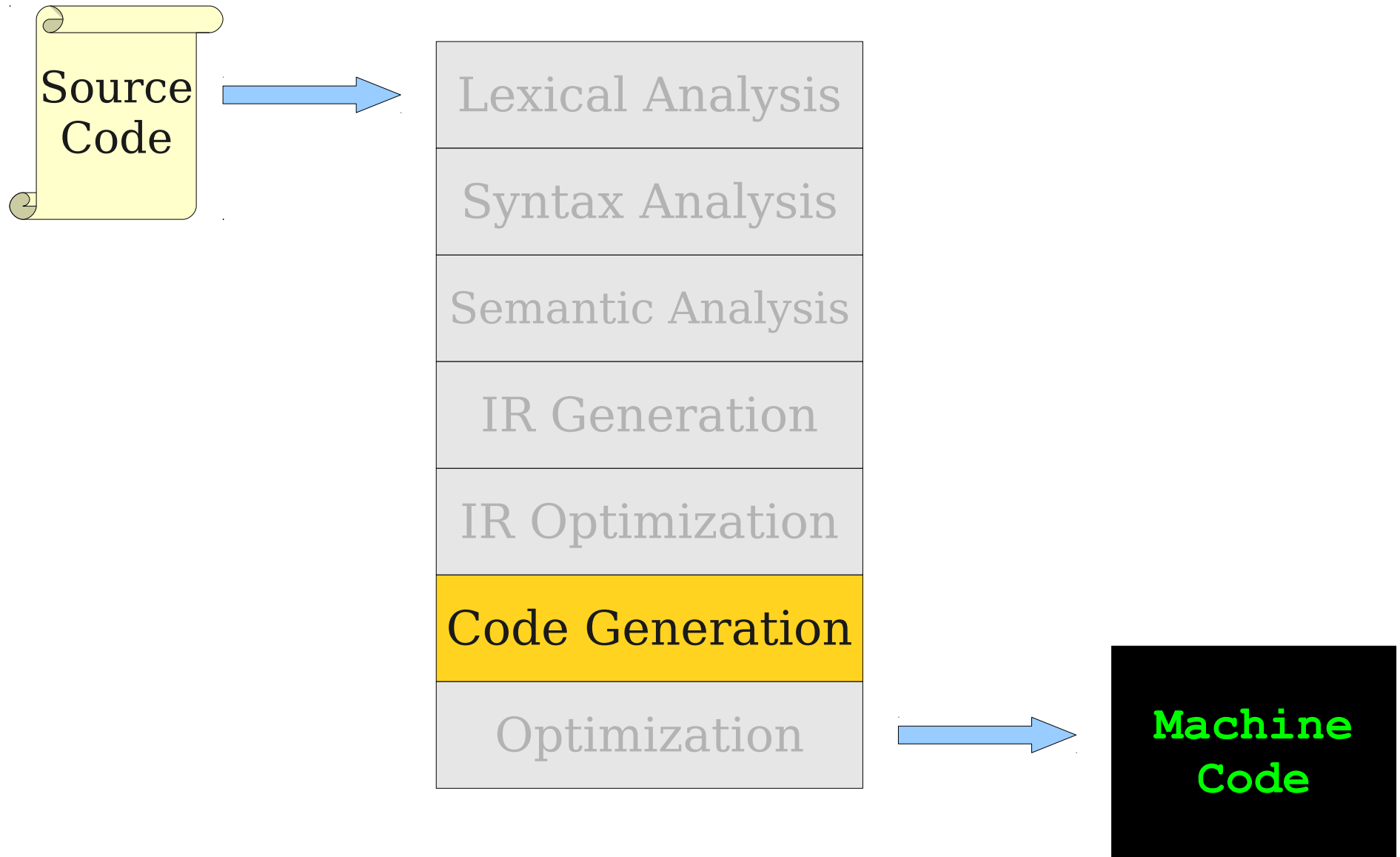


Code Optimization

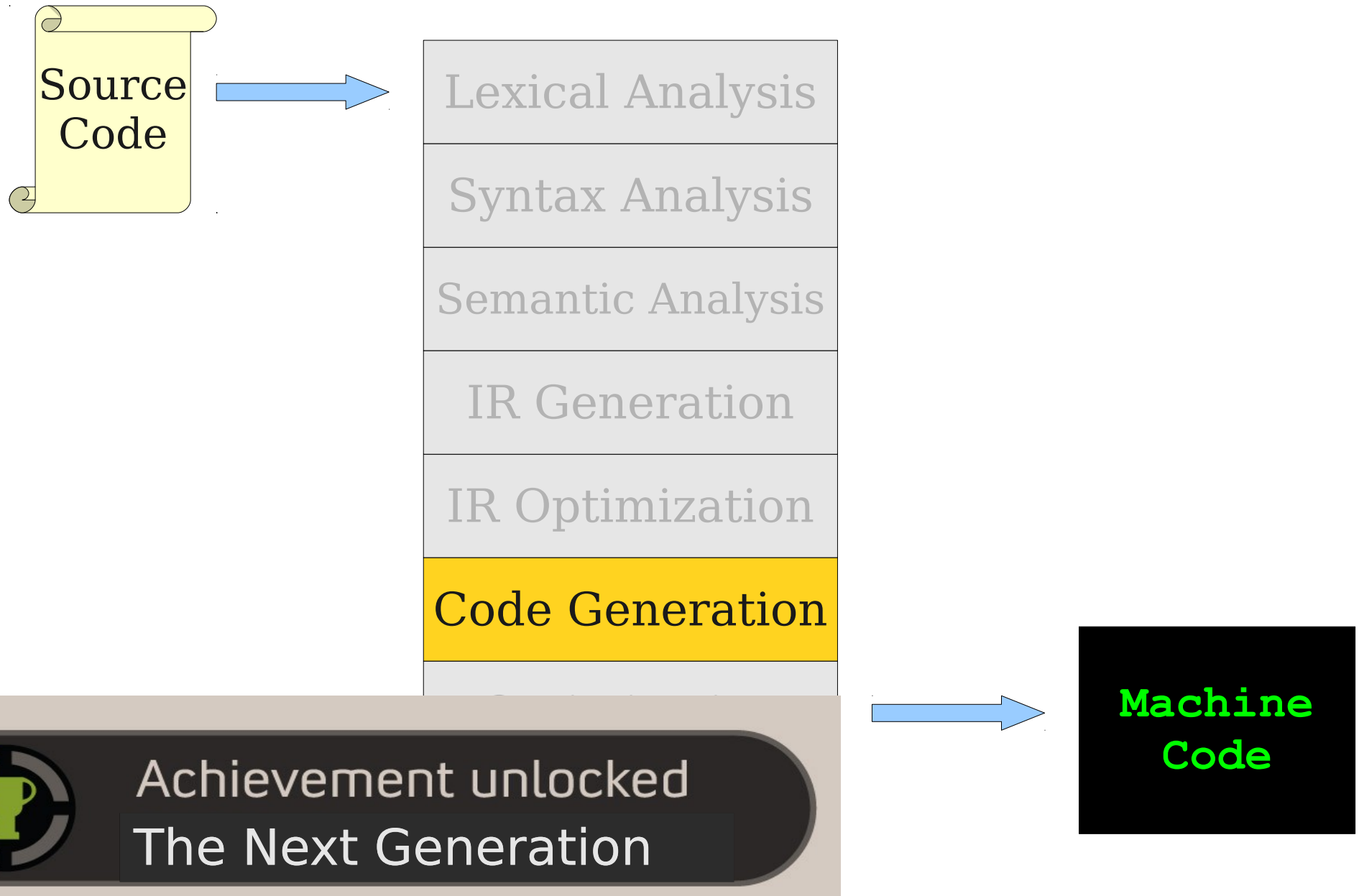
Announcements

- Programming Project 4 due Saturday at 11:30AM.
 - Stop by office hours!
 - Ask questions via email!
 - Ask questions via Piazza!
- Keith has extra office hours this Wednesday and Friday from 2PM - 4PM.
- Online course evaluation available on Axxess.
 - Please give feedback!

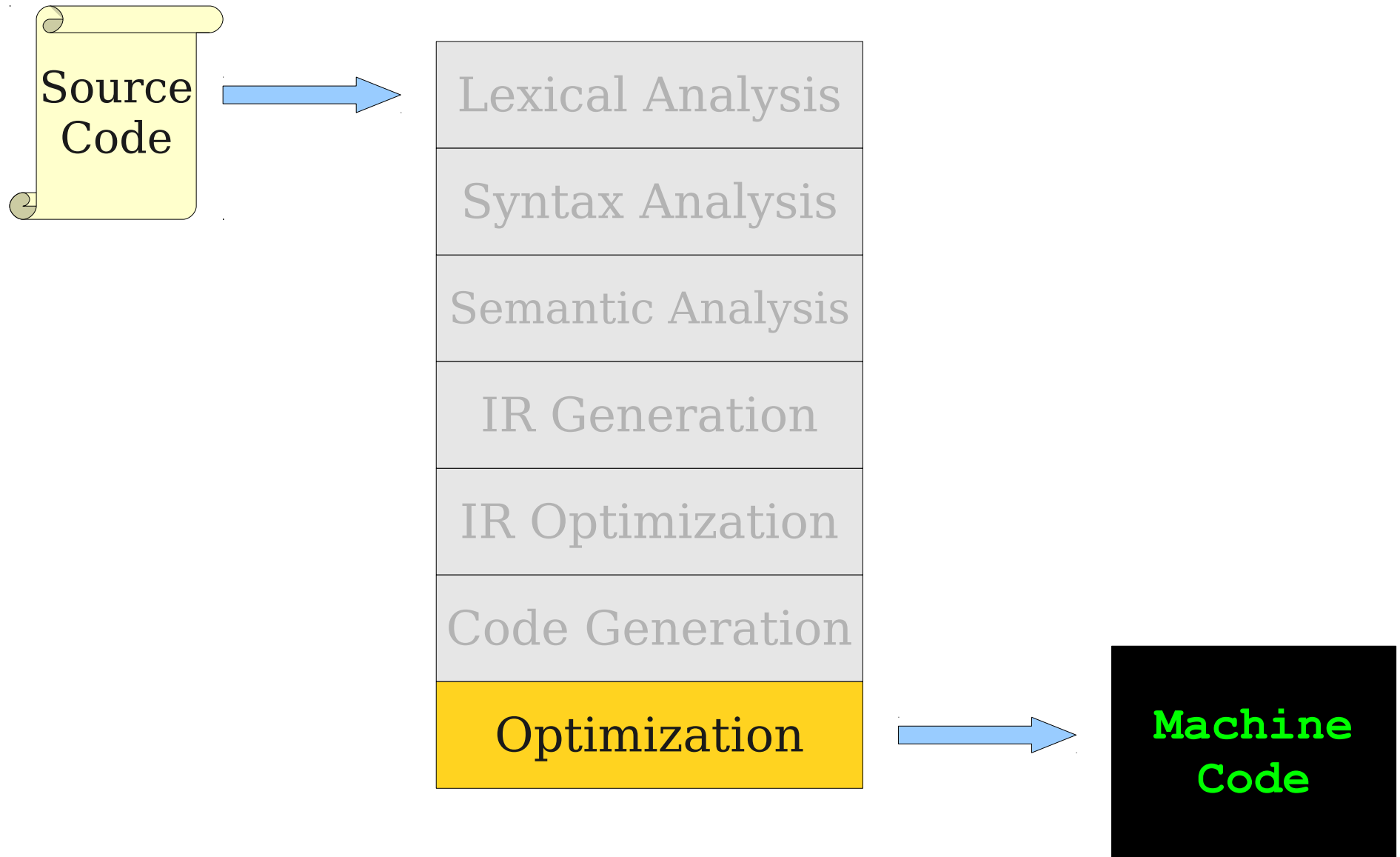
Where We Are



Where We Are



Where We Are



Final Code Optimization

- **Goal:** Optimize generated code by exploiting machine-dependent properties not visible at the IR level.
- Critical step in most compilers, but often very messy:
 - Techniques developed for one machine may be completely useless on another.
 - Techniques developed for one language may be completely useless with another.

Outline

- Goals for Today:
 - Explore important properties of machines and how they impact performance.
 - Survey common optimization techniques and the theory behind them.
 - Motivate you to take CS243 to learn more!
- Non-Goals for Today:
 - Explore tricky details of the algorithms.

Optimizations for Pipelining

Processor Pipelines

Processor Pipelines

```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t5, $t3, $t4    # $t5 = $t3 + $t4
add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

Processor Pipelines

**Instruction
Decoder**

```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t5, $t3, $t4    # $t5 = $t3 + $t4
add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

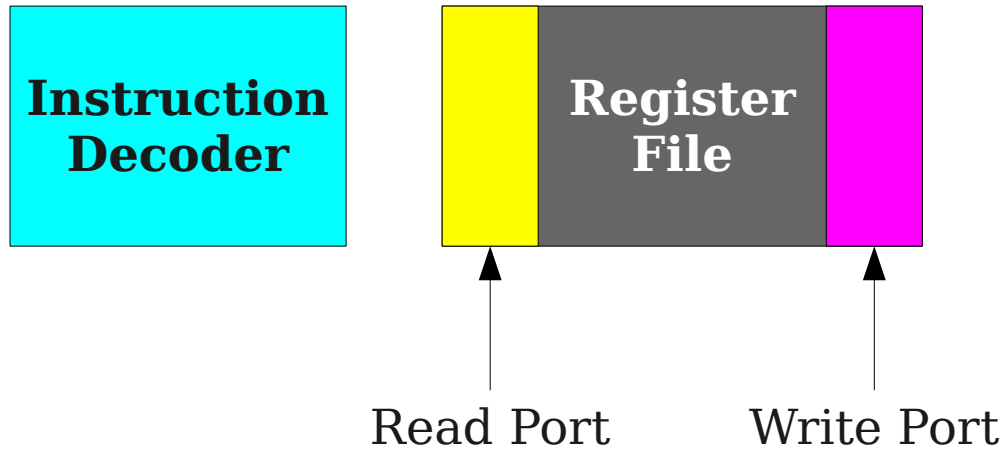
Processor Pipelines

**Instruction
Decoder**

**Register
File**

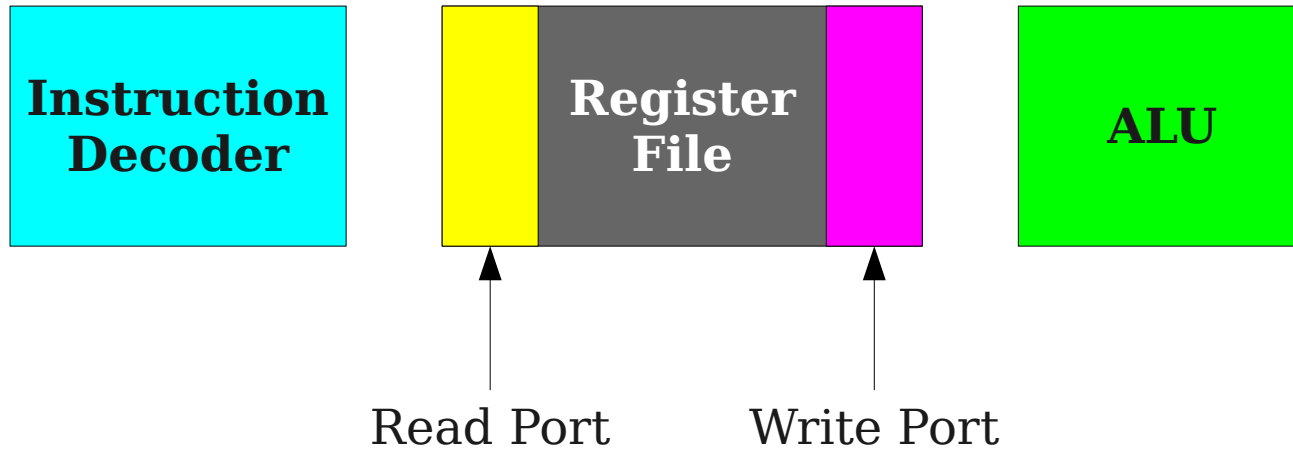
```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t5, $t3, $t4    # $t5 = $t3 + $t4
add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

Processor Pipelines



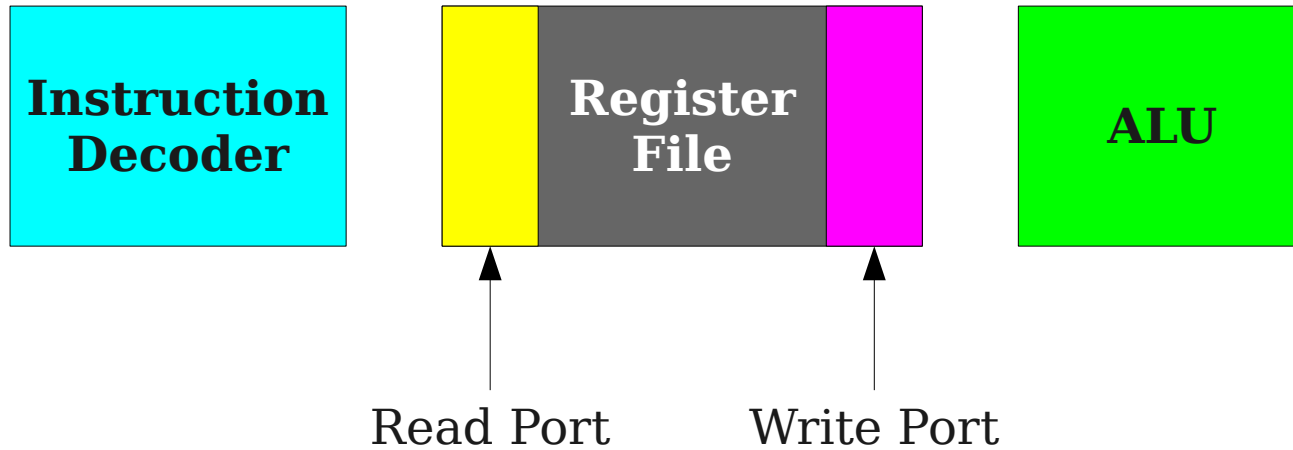
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add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

Processor Pipelines



```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
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add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

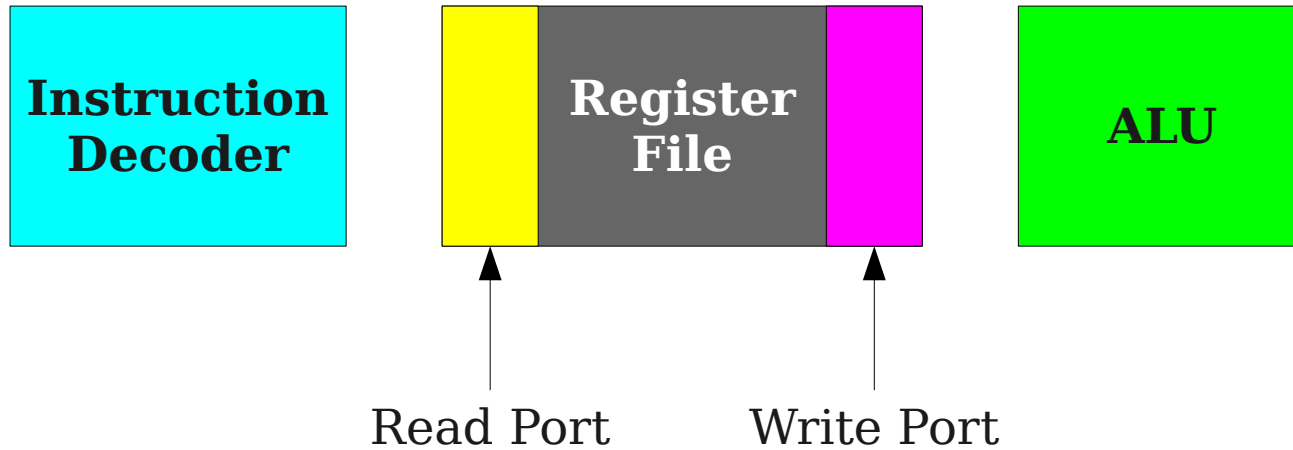
Processor Pipelines



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add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

[illegible]

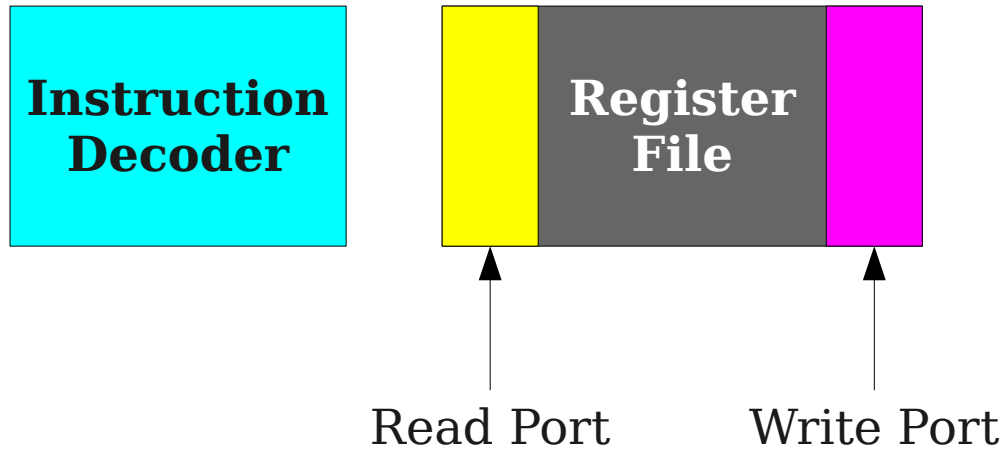
Processor Pipelines



```
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add $t5, $t3, $t4    # $t5 = $t3 + $t4
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```

[illegible]

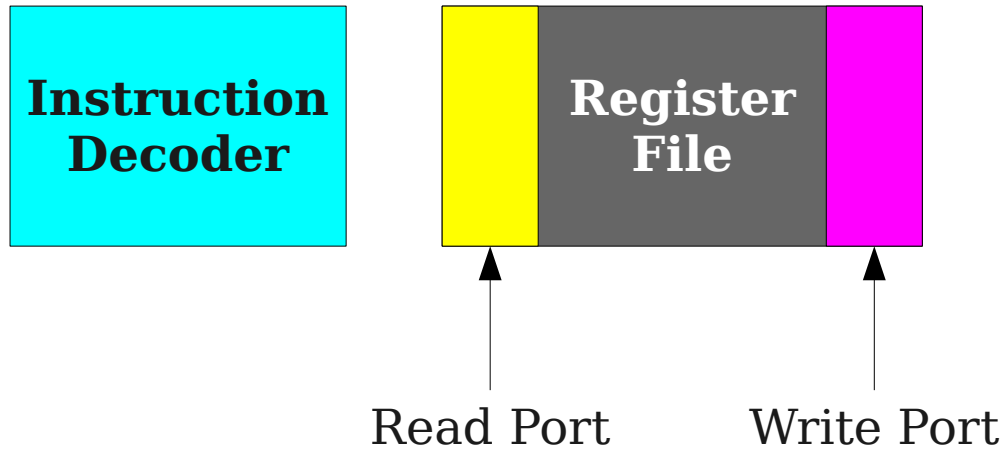
Processor Pipelines



```
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add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

[illegible]

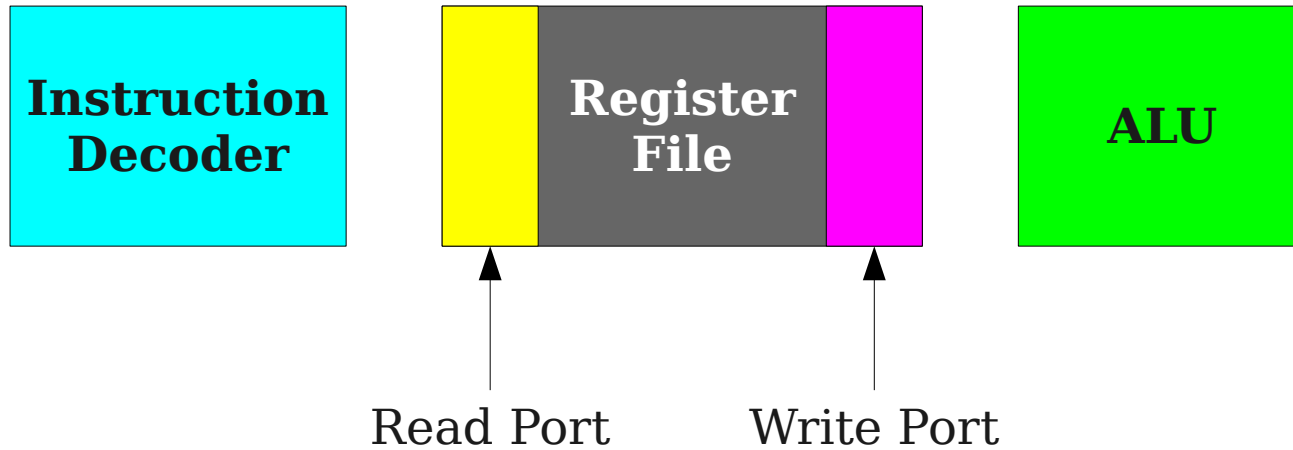
Processor Pipelines



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```

ID	RR	ALU	RW

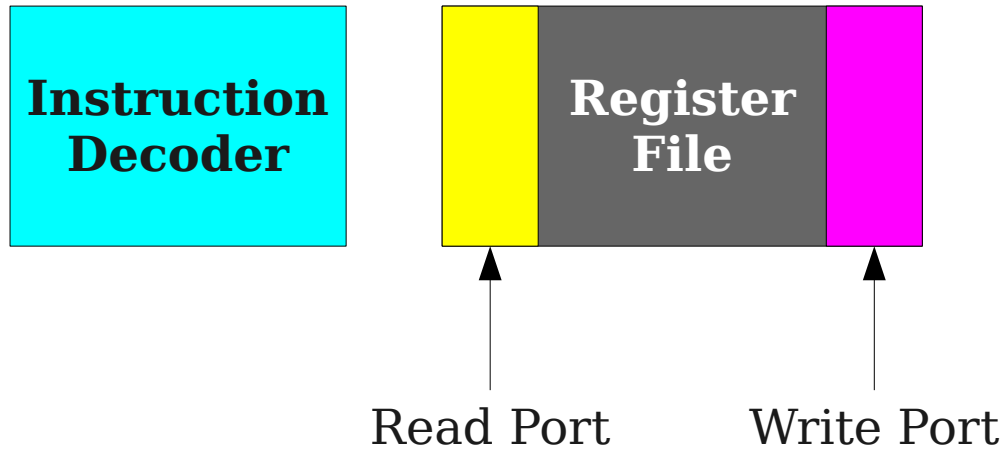
Processor Pipelines



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```

ID	RR	ALU	RW

Processor Pipelines

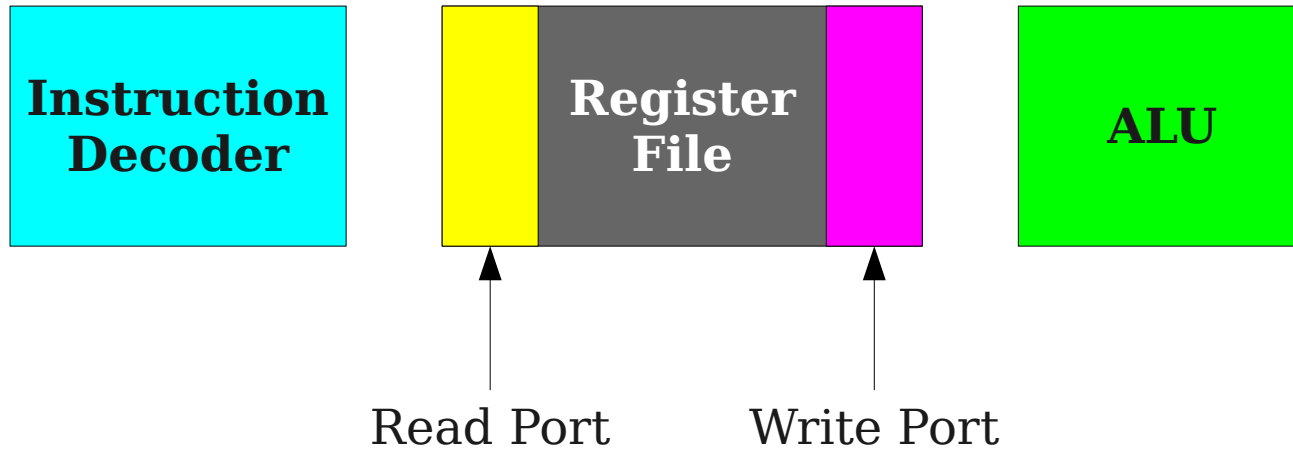


```
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add $t5, $t3, $t4    # $t5 = $t3 + $t4
add $t8, $t6, $t7    # $t8 = $t6 + $t7
```

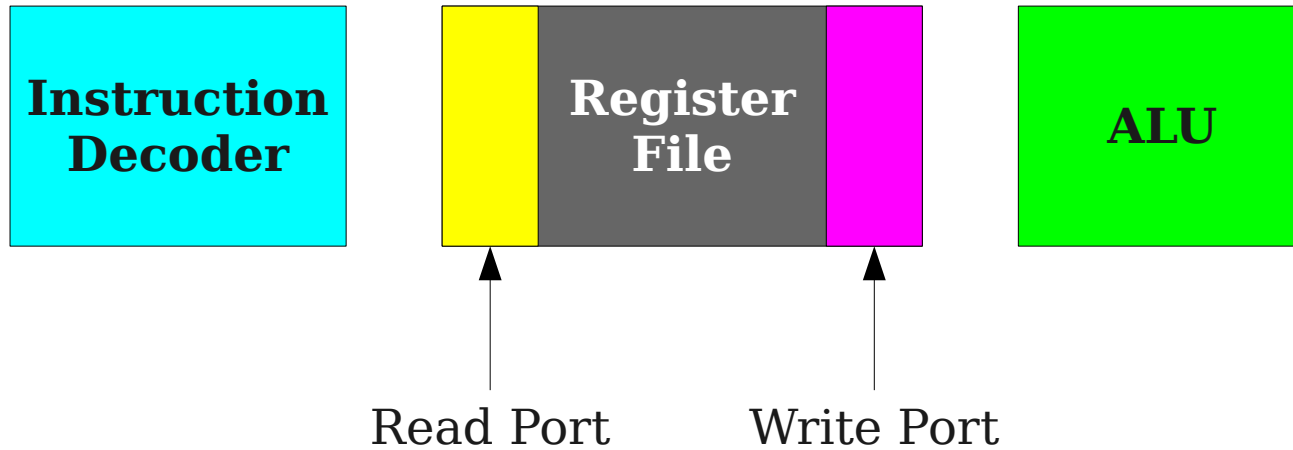
[illegible]

Pipeline Hazards

Pipeline Hazards

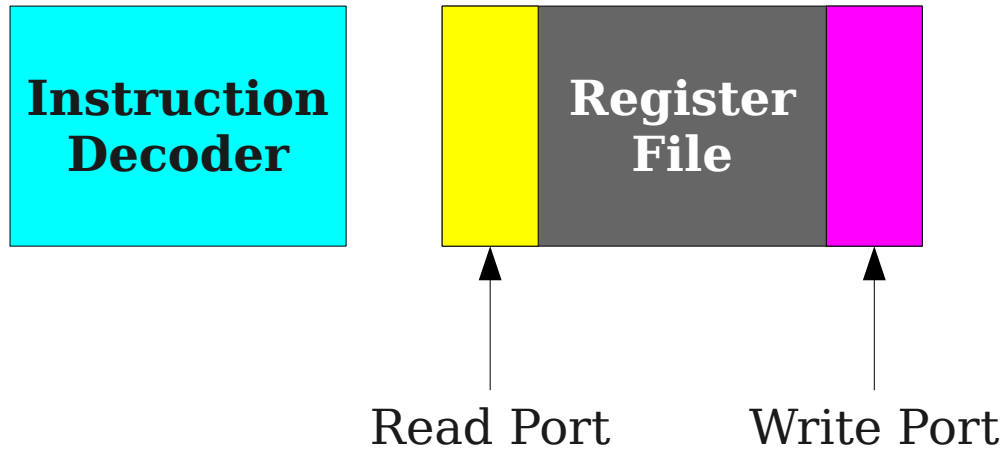


Pipeline Hazards



```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

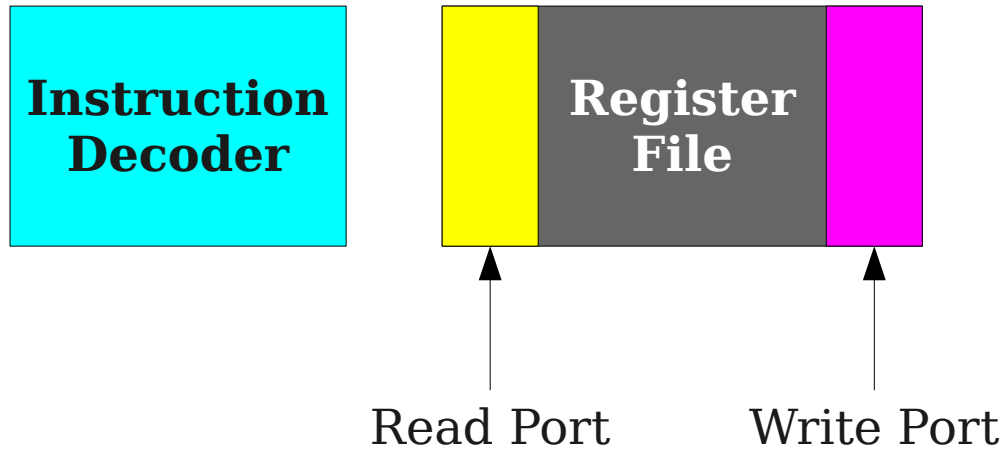
Pipeline Hazards



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add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

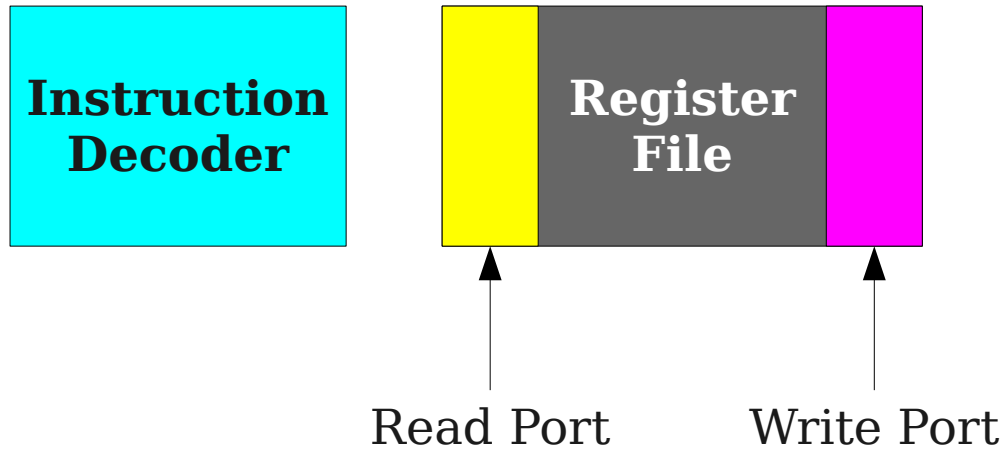
Pipeline Hazards



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add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

Pipeline Hazards

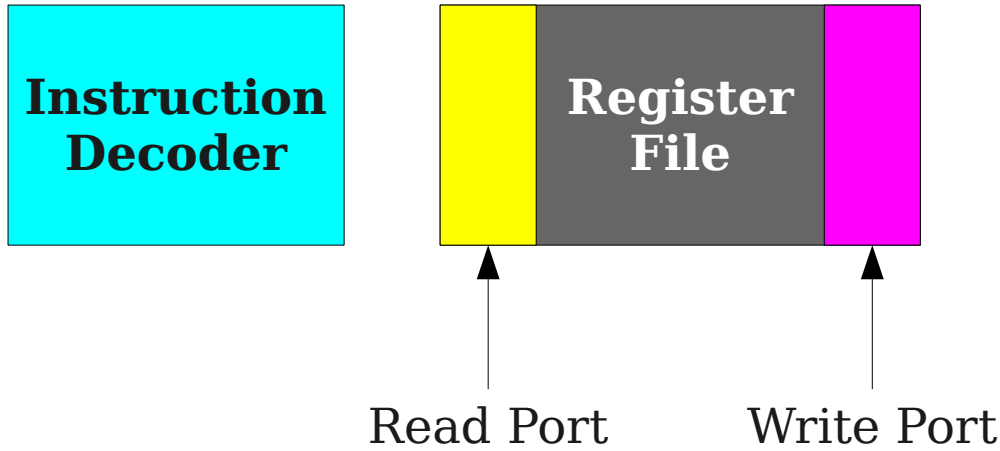


```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

Pipeline Hazards

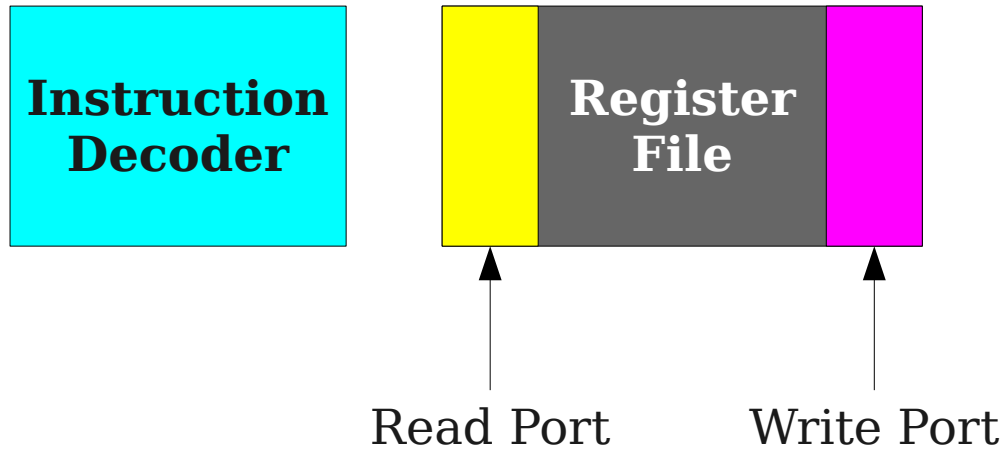
This value isn't ready yet!



```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

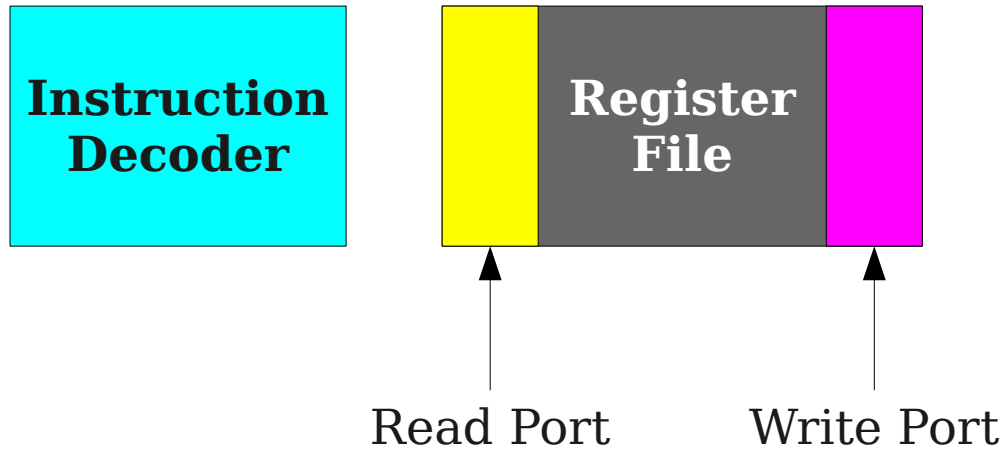
Pipeline Hazards



```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
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add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

Pipeline Hazards

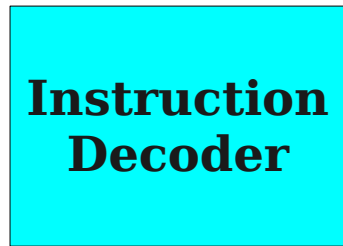


```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

ID	RR	ALU	RW

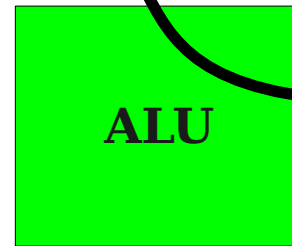
Pipeline Hazards

stall pipeline until
value is ready



Read Port

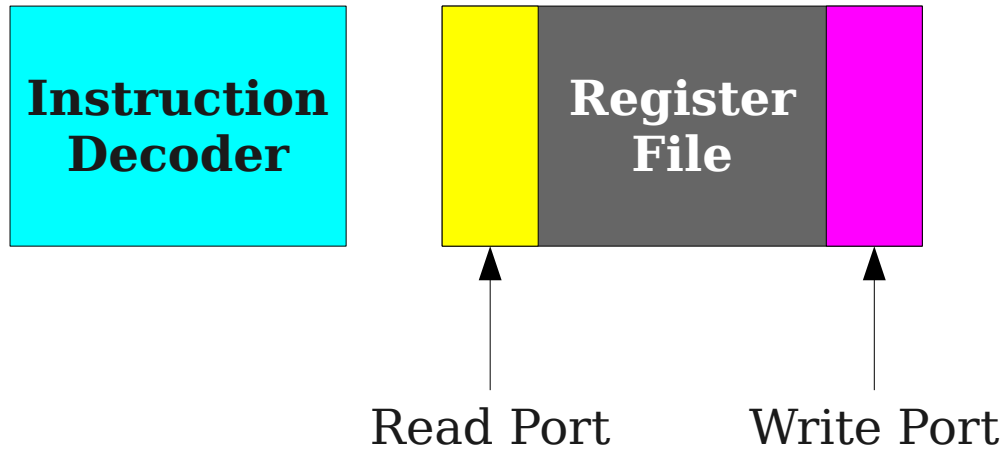
Write Port



	ID	RR	ALU	RW
	Red	White	White	White
	Green	Red	White	White
▶	Green	White	Red	White
	Green	White	White	Red
	White	Green	White	White
	White	White	Green	White
	White	White	White	Green
	White	White	White	White
	White	White	White	White
	White	White	White	White
	White	White	White	White

```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

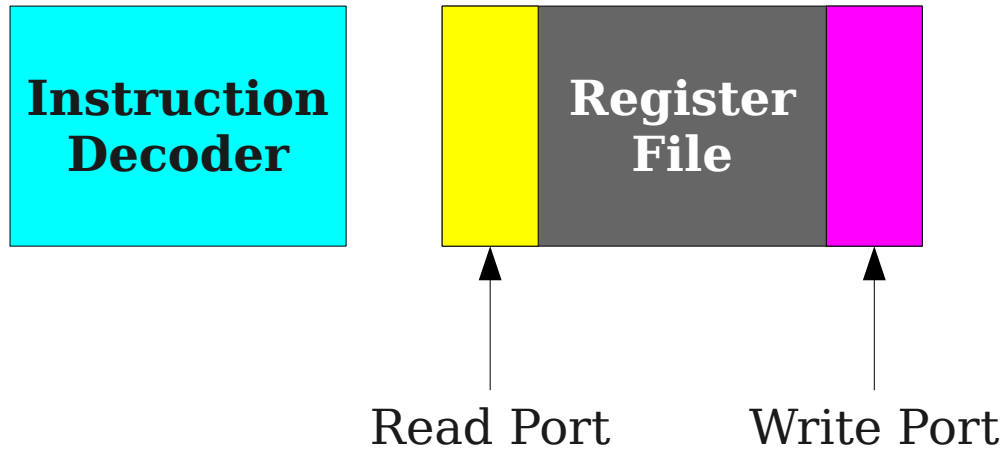
Pipeline Hazards



```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

ID	RR	ALU	RW

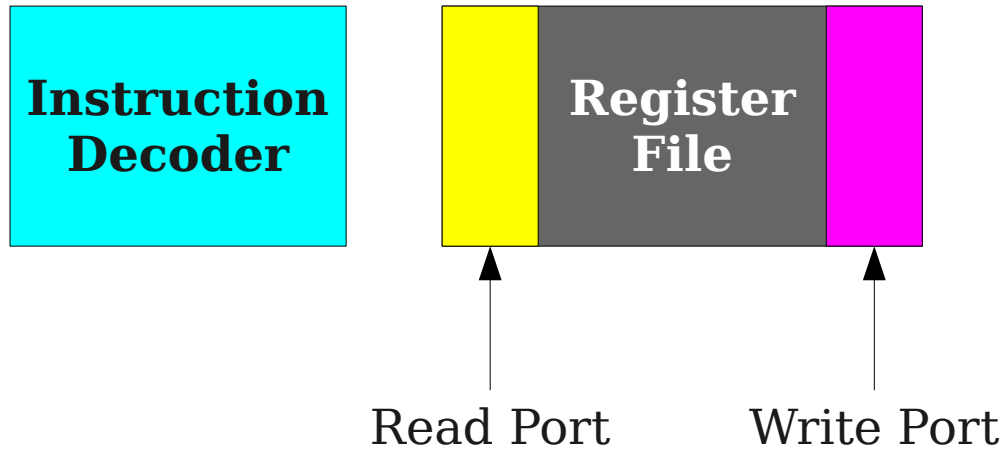
Pipeline Hazards



```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

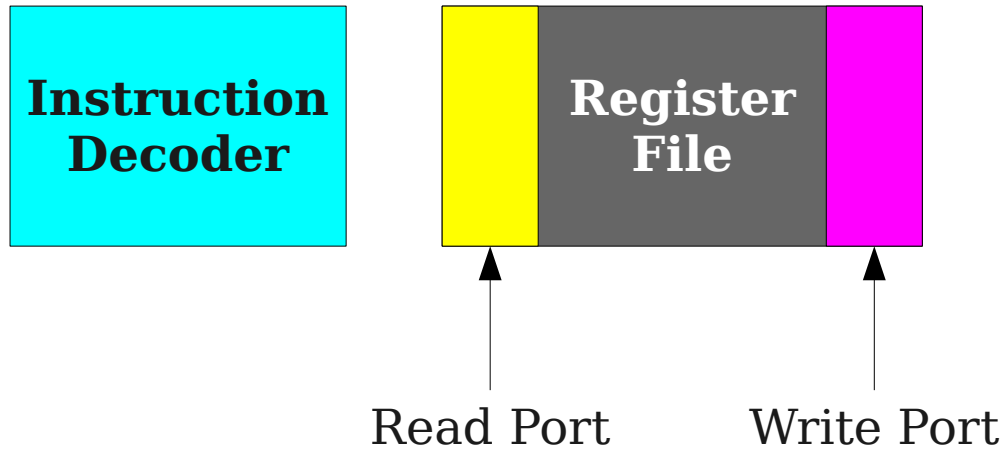
Pipeline Hazards



```
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add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

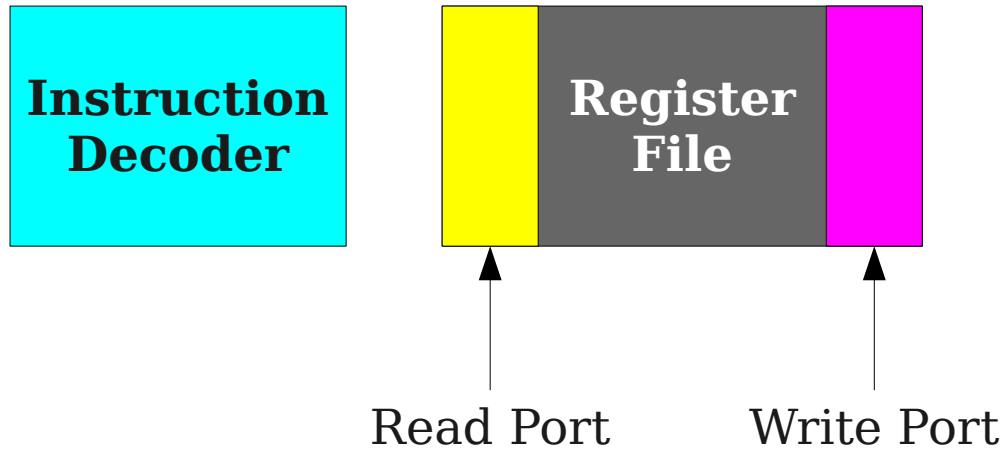
Pipeline Hazards



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```

[illegible]

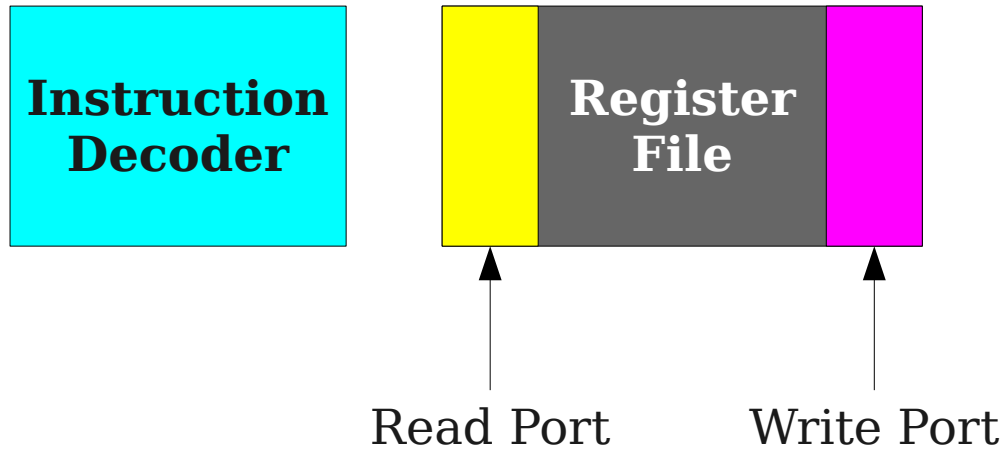
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add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

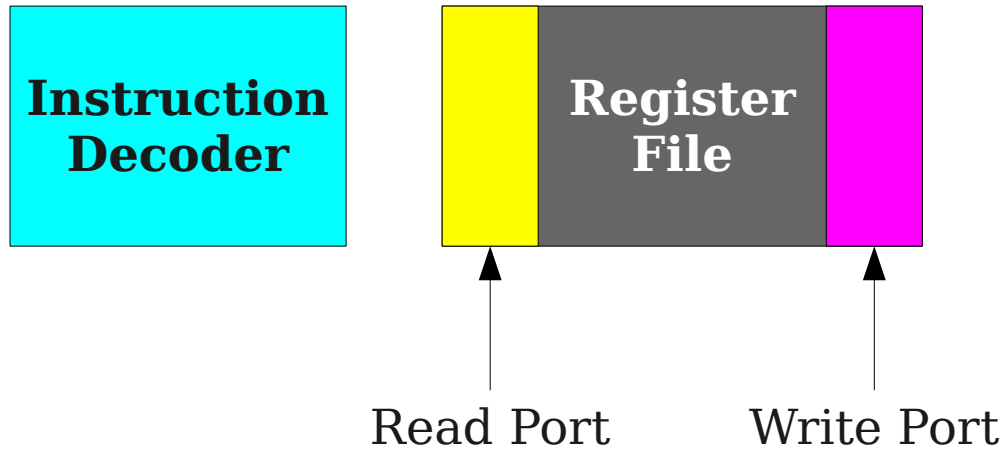
Pipeline Hazards



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add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

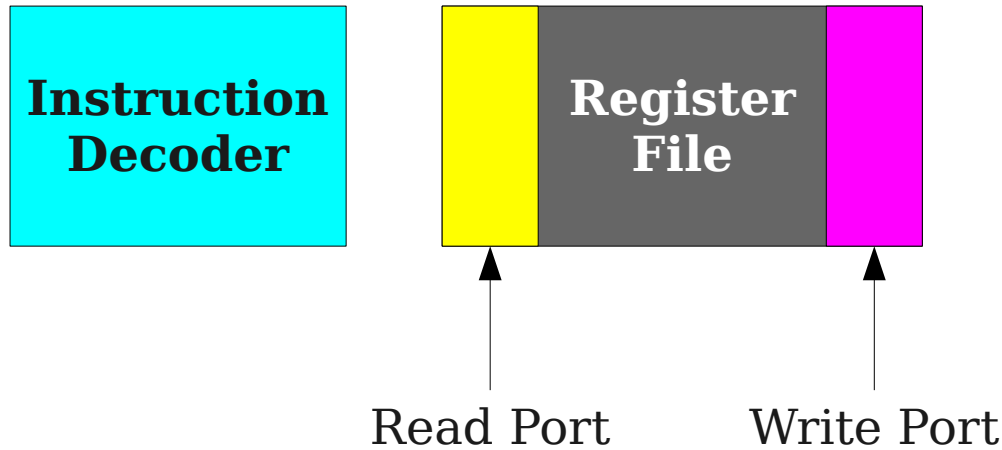
Pipeline Hazards



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add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

[illegible]

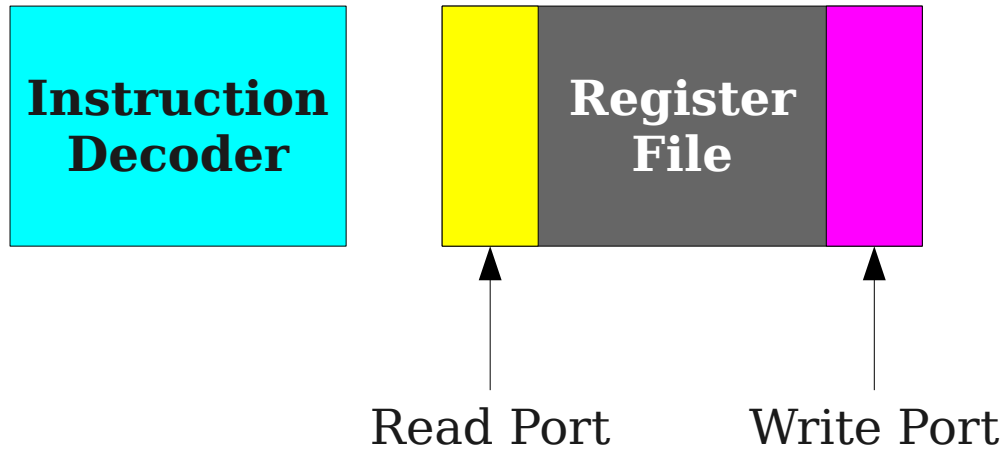
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```

ID	RR	ALU	RW

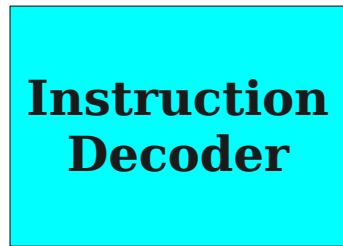
Pipeline Hazards



```
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add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

ID	RR	ALU	RW

Pipeline Hazards



Read Port

Write Port

```
add $t2, $t0, $t1    # $t2 = $t0 + $t1
add $t7, $t5, $t6    # $t7 = $t5 + $t6
add $t4, $t3, $t2    # $t5 = $t3 + $t2
add $t0, $t0, $t7    # $t0 = $t0 + $t7
```

Two clock
cycles faster!

ID	RR	ALU	RW

Instruction Scheduling

- Because of processor pipelining, the order in which instructions are executed can impact performance.
- **Instruction scheduling** is the reordering or insertion of machine instructions to increase performance.
- All good optimizing compilers have some sort of instruction scheduling support.

Data Dependencies

- A **data dependency** in machine code is a set of instructions whose behavior depends on one another.
- Intuitively, a set of instructions that cannot be reordered around each other.
- Three types of data dependencies:

**Read-after-Write
(RAW)**

$x = \dots$
 $\dots = x$

**Write-after-Read
(WAR)**

$\dots = x$
 $x = \dots$

**Write-after-Write
(WAW)**

$x = \dots$
 $x = \dots$

Finding Data Dependencies

$$t0 = t1 + t2$$

$$t1 = t0 + t1$$

$$t3 = t2 + t4$$

$$t0 = t1 + t2$$

$$t5 = t3 + t4$$

$$t6 = t2 + t3$$

Finding Data Dependencies

$$t0 = t1 + t2$$

$$t1 = t0 + t1$$

$$t3 = t2 + t4$$

$$t0 = t1 + t2$$

$$t5 = t3 + t4$$

$$t6 = t2 + t7$$

Finding Data Dependencies

$$t0 = t1 + t2$$

$$t1 = t0 + t1$$

$$t3 = t2 + t4$$

$$t0 = t1 + t2$$

$$t5 = t3 + t4$$

$$t6 = t2 + t7$$

Finding Data Dependencies

$t_0 = t_1 + t_2$



$t_1 = t_0 + t_1$

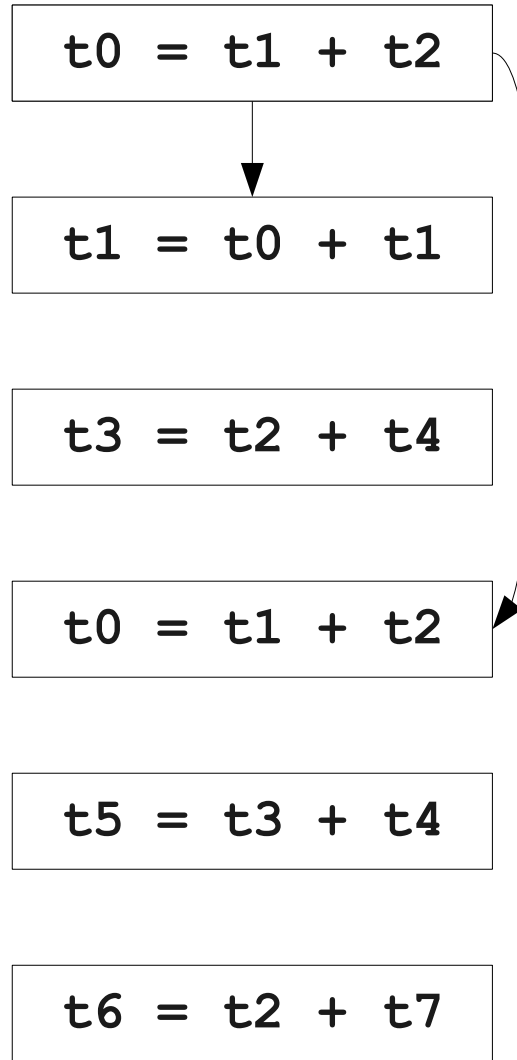
$t_3 = t_2 + t_4$

$t_0 = t_1 + t_2$

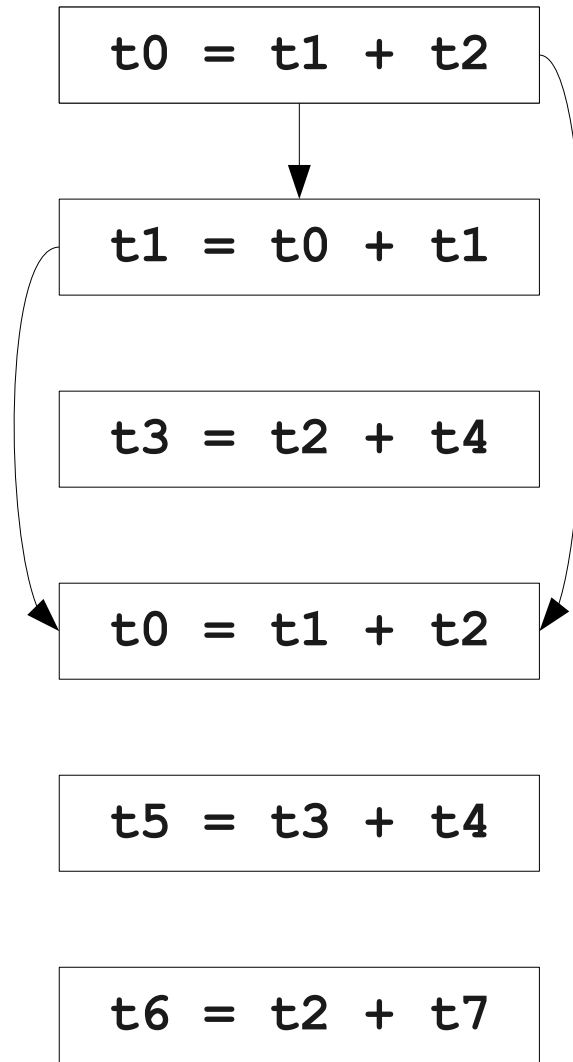
$t_5 = t_3 + t_4$

$t_6 = t_2 + t_7$

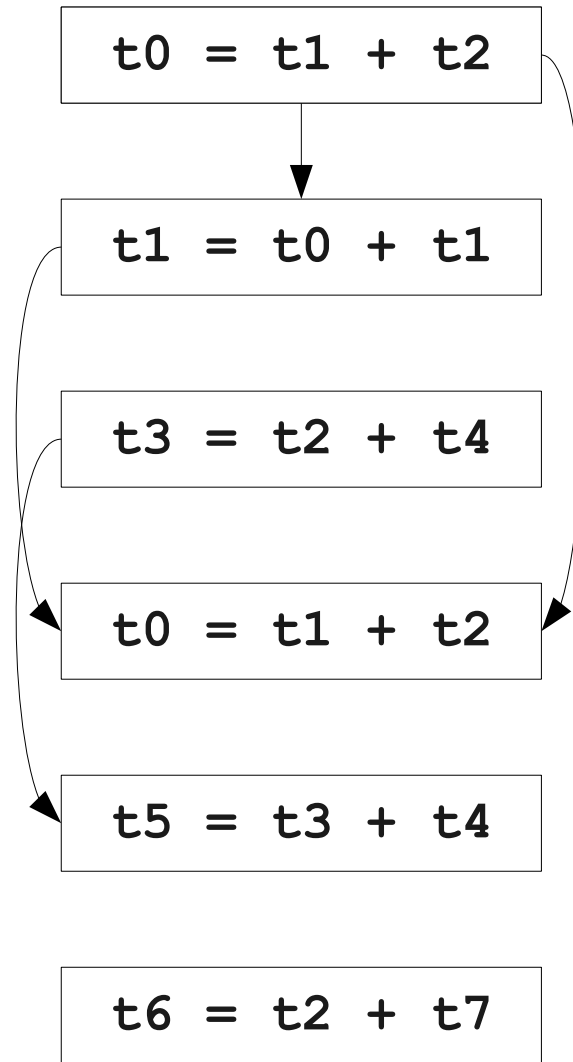
Finding Data Dependencies



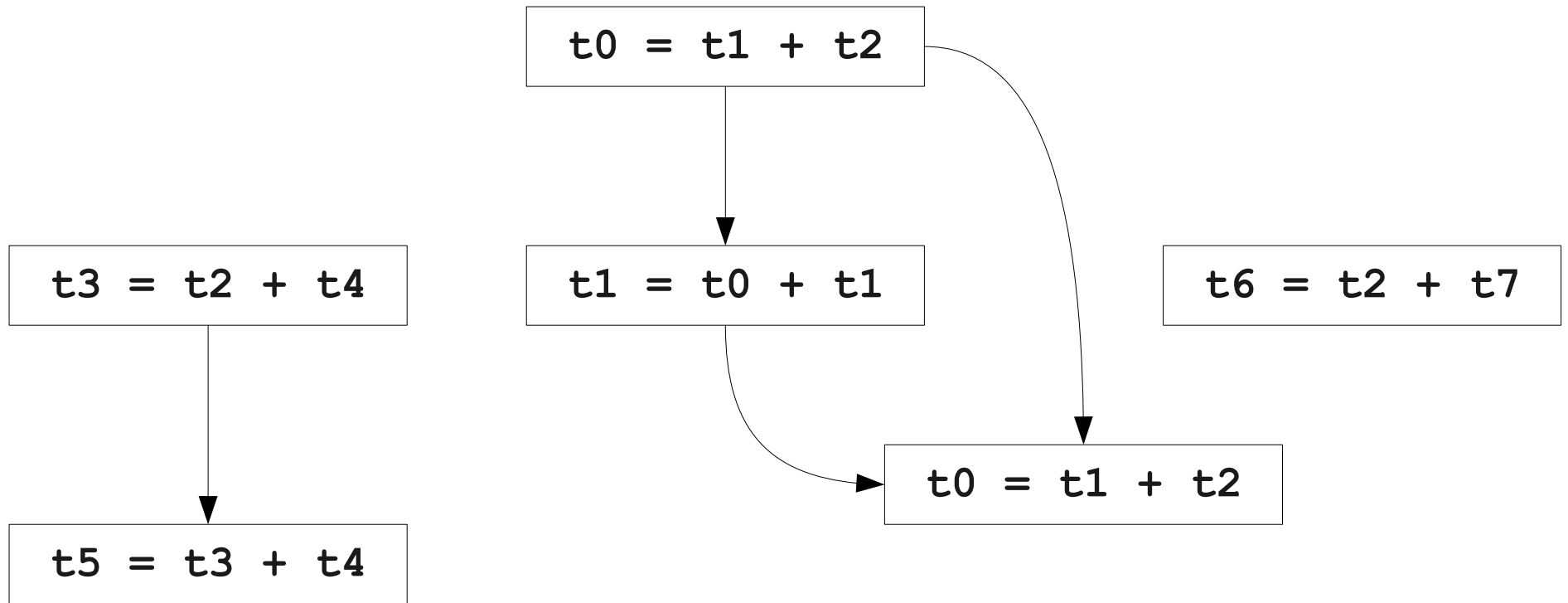
Finding Data Dependencies



Finding Data Dependencies



Finding Data Dependencies

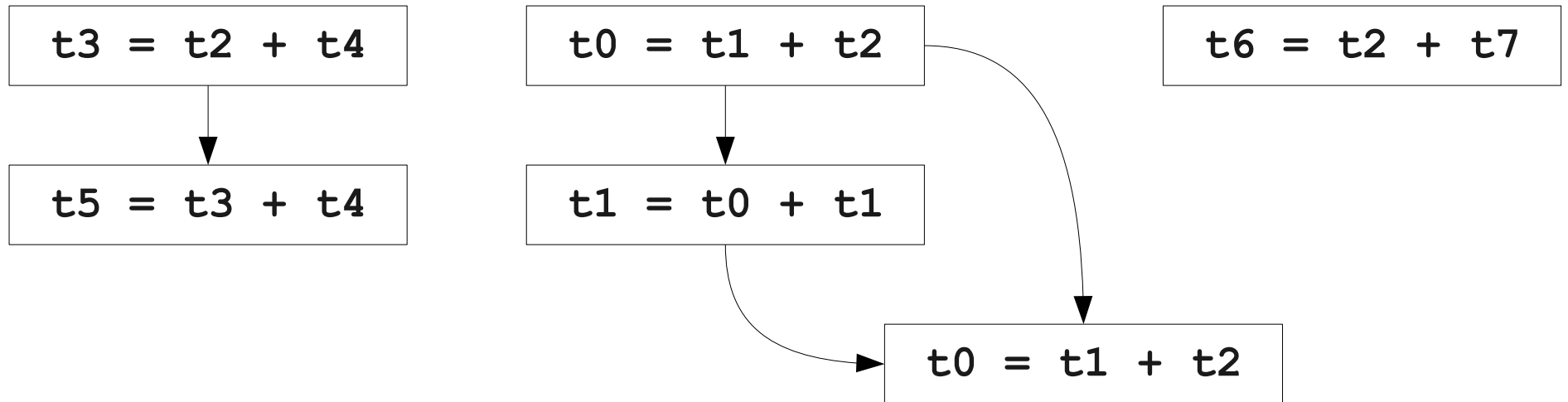


Data Dependency Graphs

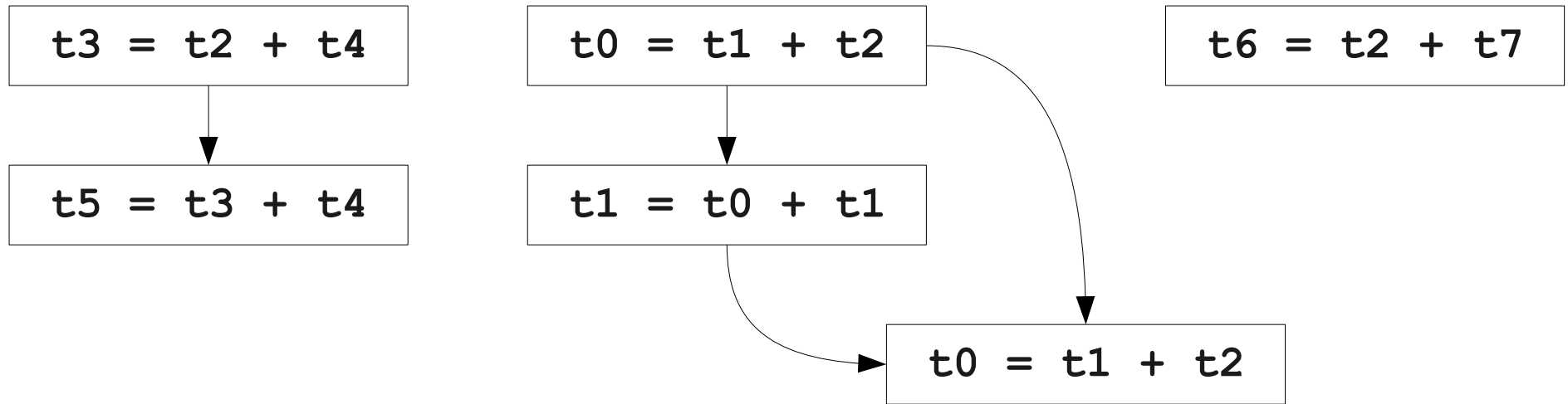
- The graph of the data dependencies in a basic block is called the **data dependency graph**.
- Always a **directed acyclic** graph:
 - **Directed**: One instruction depends on the other.
 - **Acyclic**: No circular dependencies allowed. (*Why?*)
- Can schedule instructions in a basic block in any order as long as we never schedule a node before all its parents.
- **Idea**: Do a **topological sort** of the data dependency graph and output instructions in that order.

Instruction Scheduling

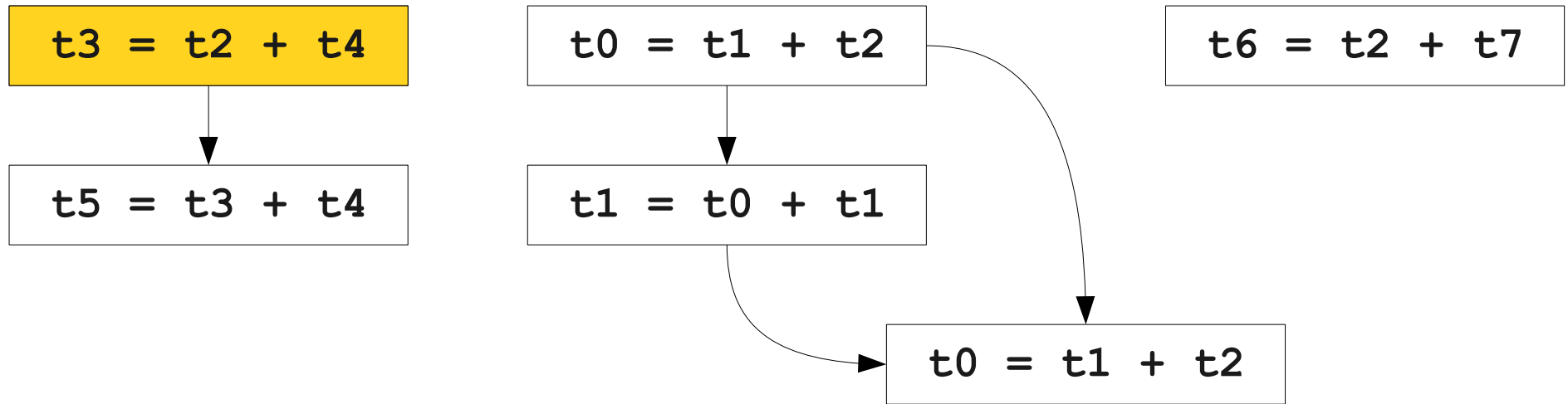
Instruction Scheduling



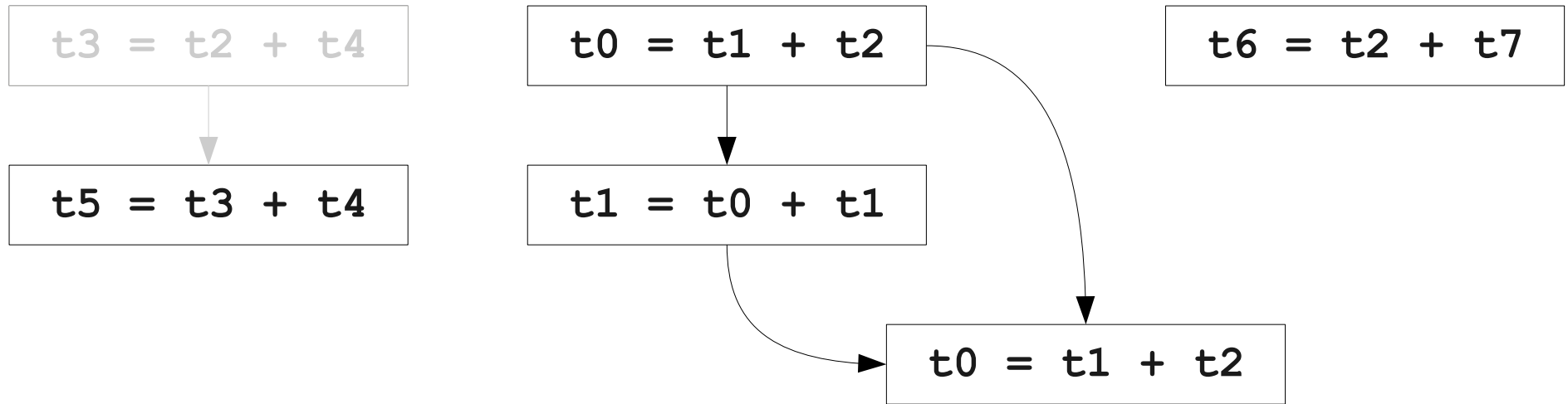
Instruction Scheduling



Instruction Scheduling

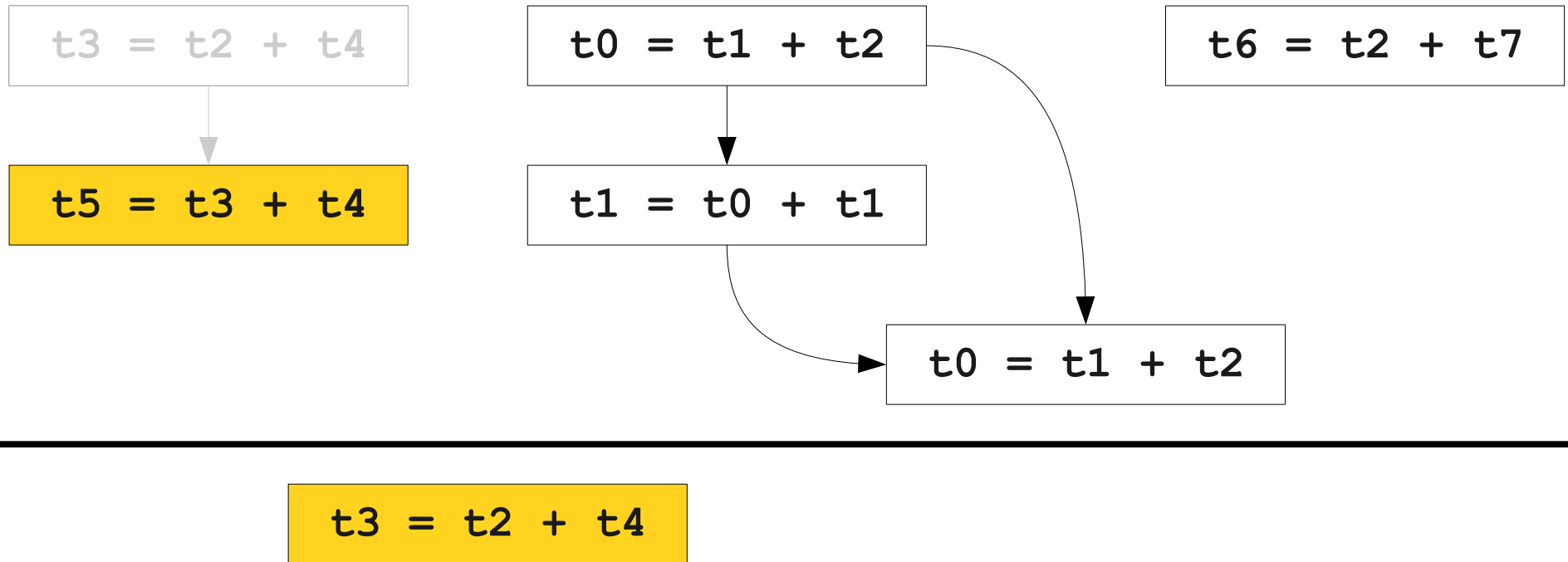


Instruction Scheduling

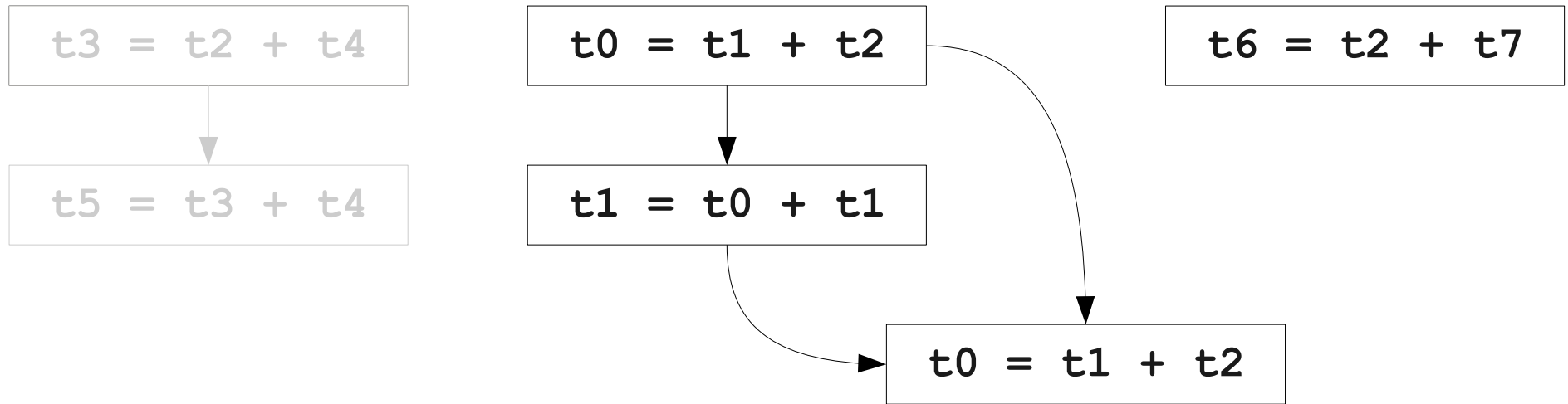


$t3 = t2 + t4$

Instruction Scheduling



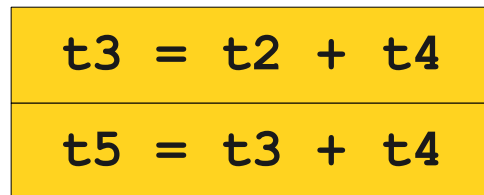
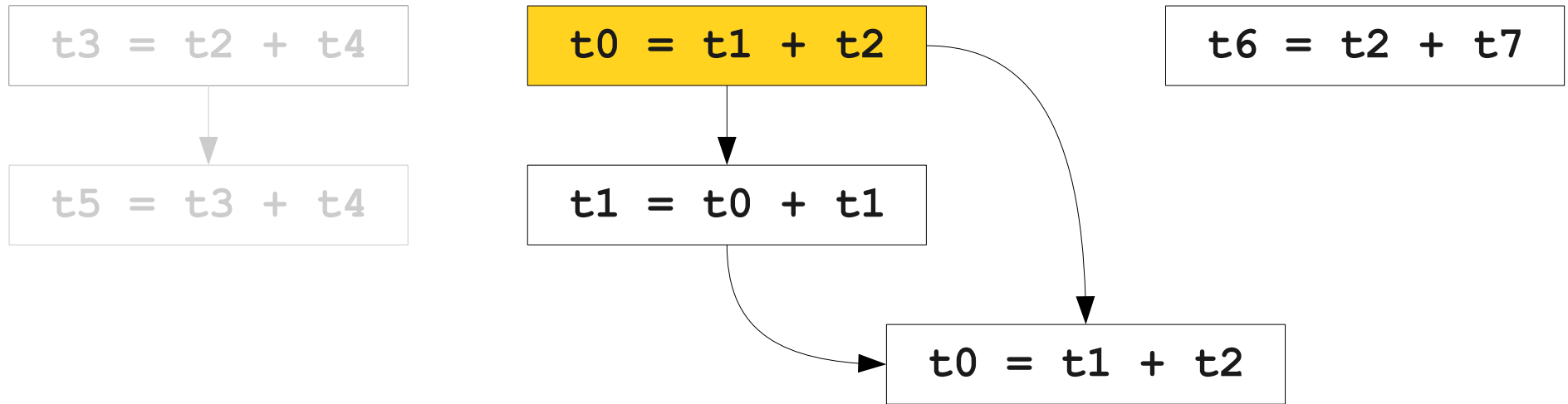
Instruction Scheduling



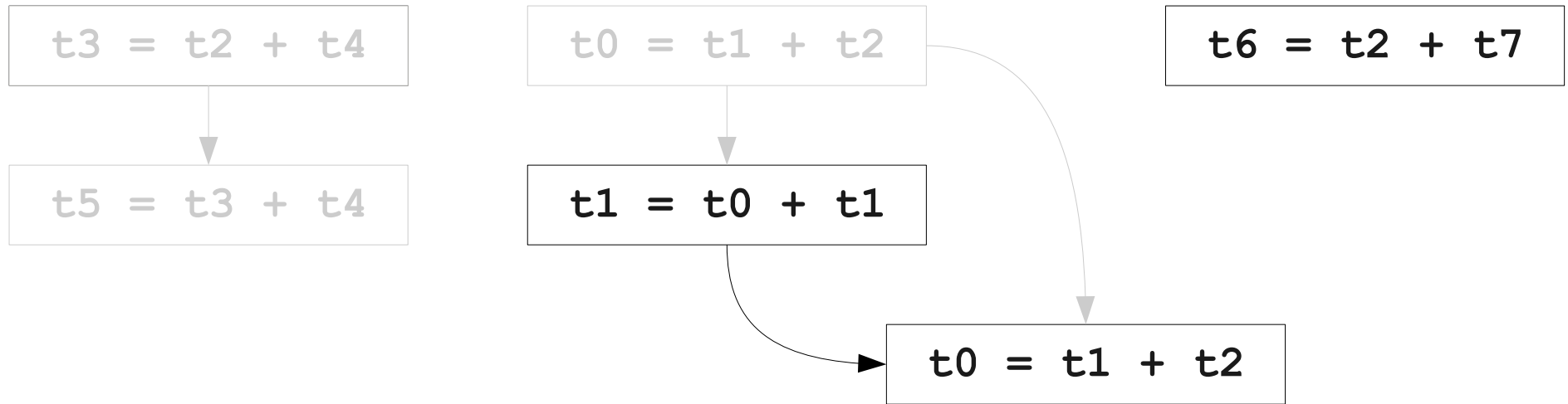
$t3 = t2 + t4$

$t5 = t3 + t4$

Instruction Scheduling

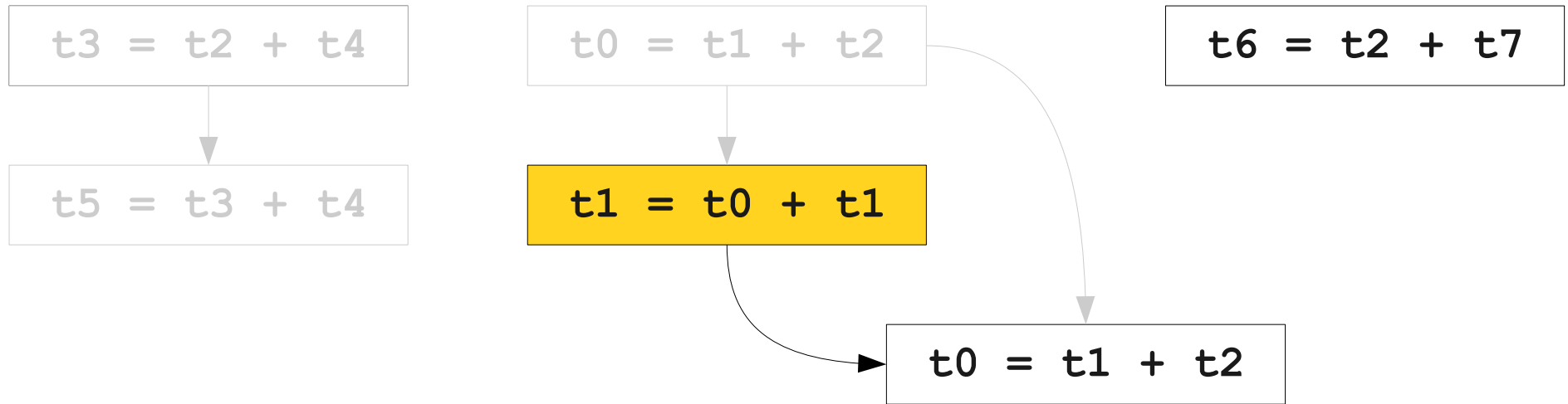


Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$

Instruction Scheduling

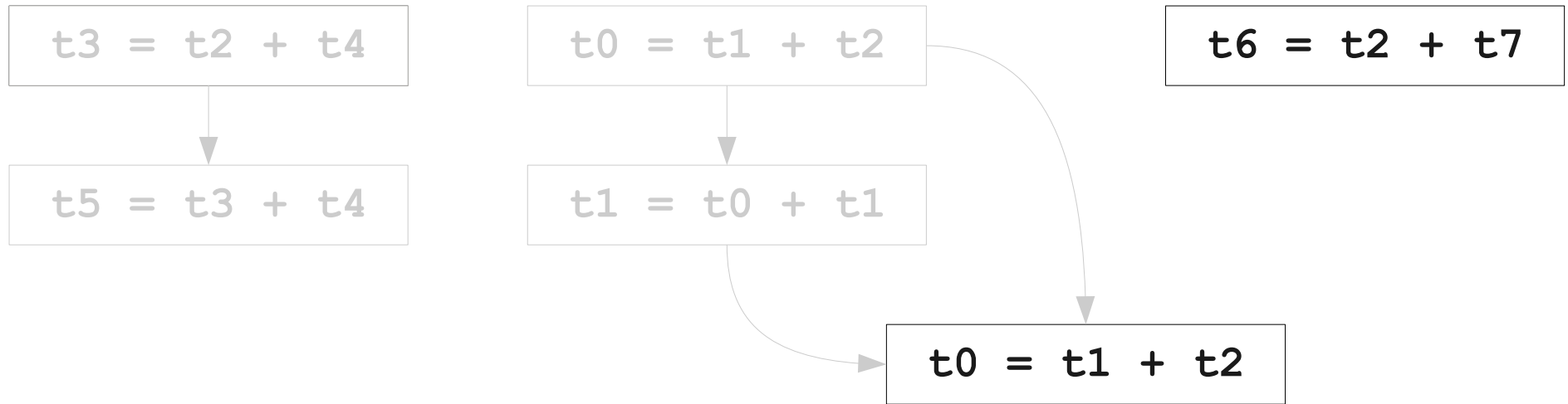


$t3 = t2 + t4$

$t5 = t3 + t4$

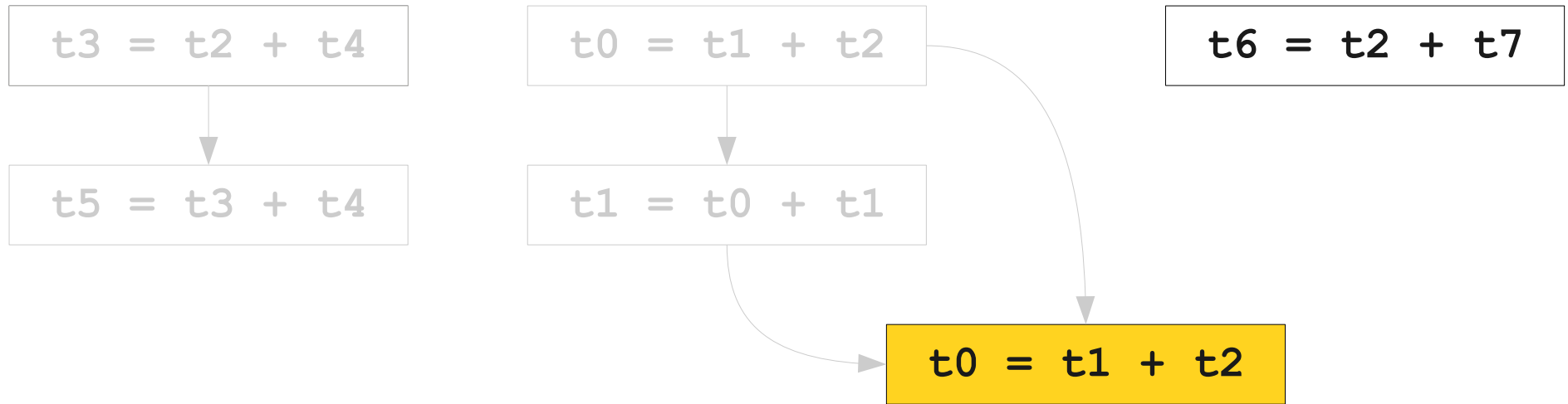
$t0 = t1 + t2$

Instruction Scheduling



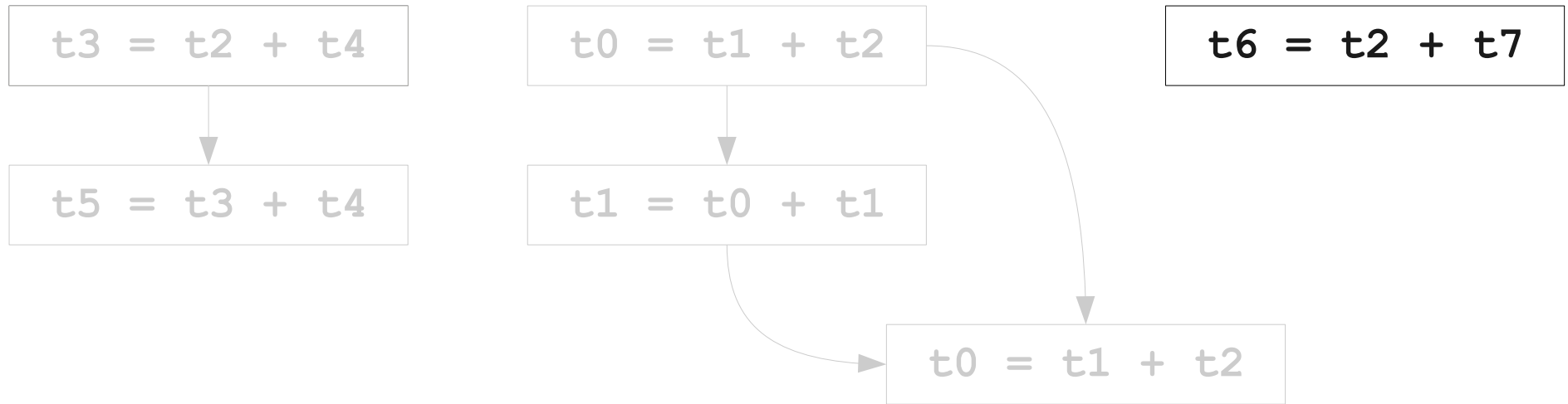
$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$

Instruction Scheduling



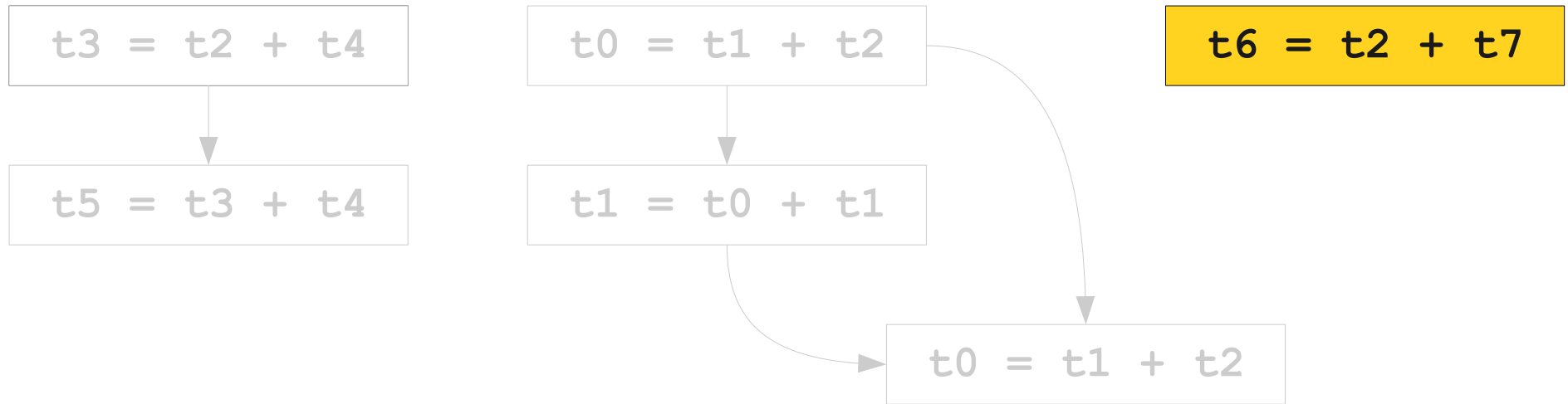
$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$

Instruction Scheduling



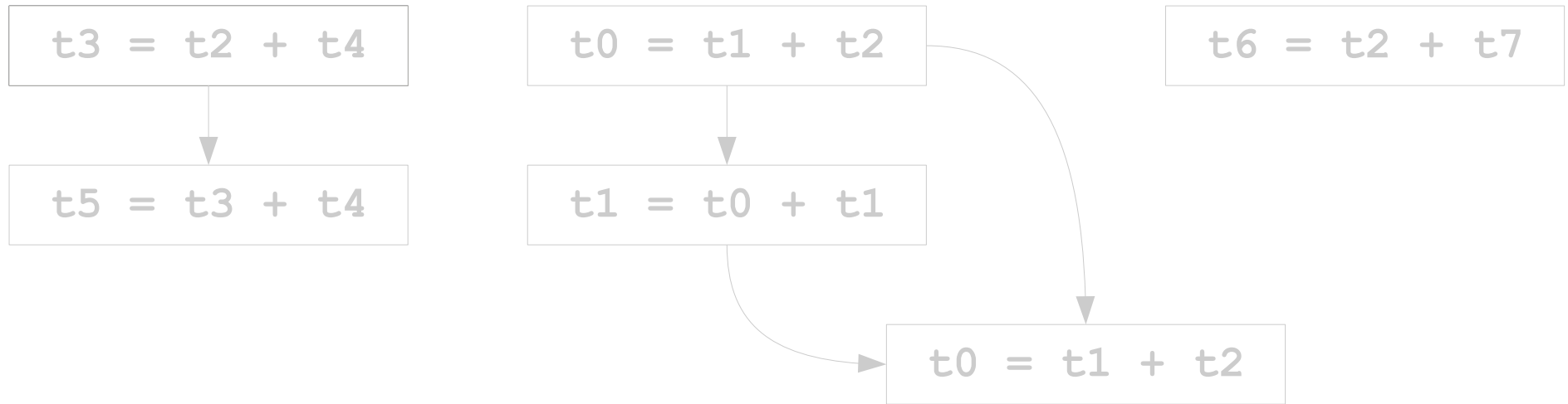
$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$

Instruction Scheduling



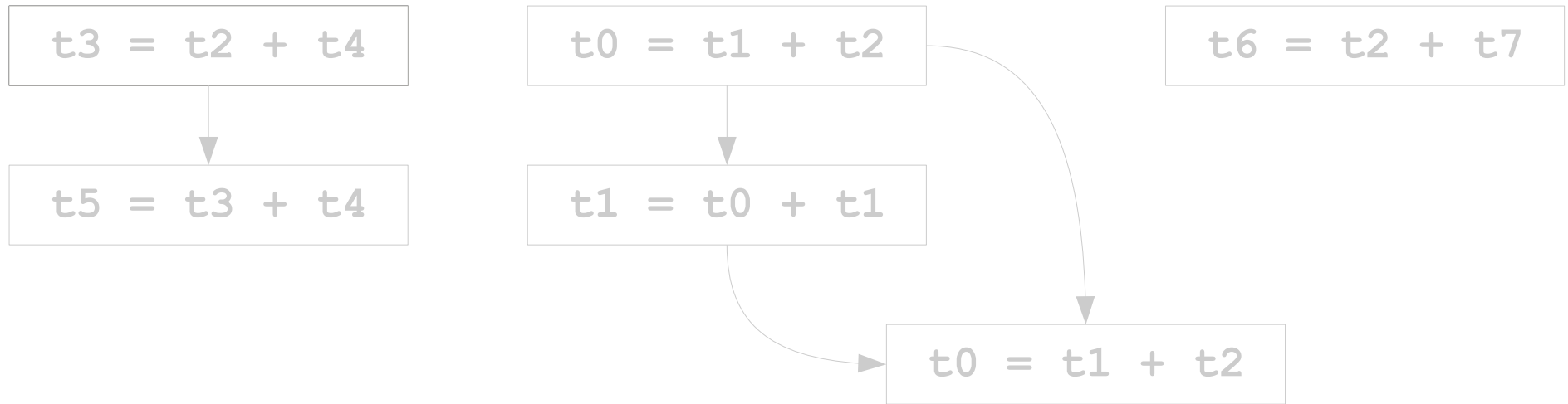
$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$

Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

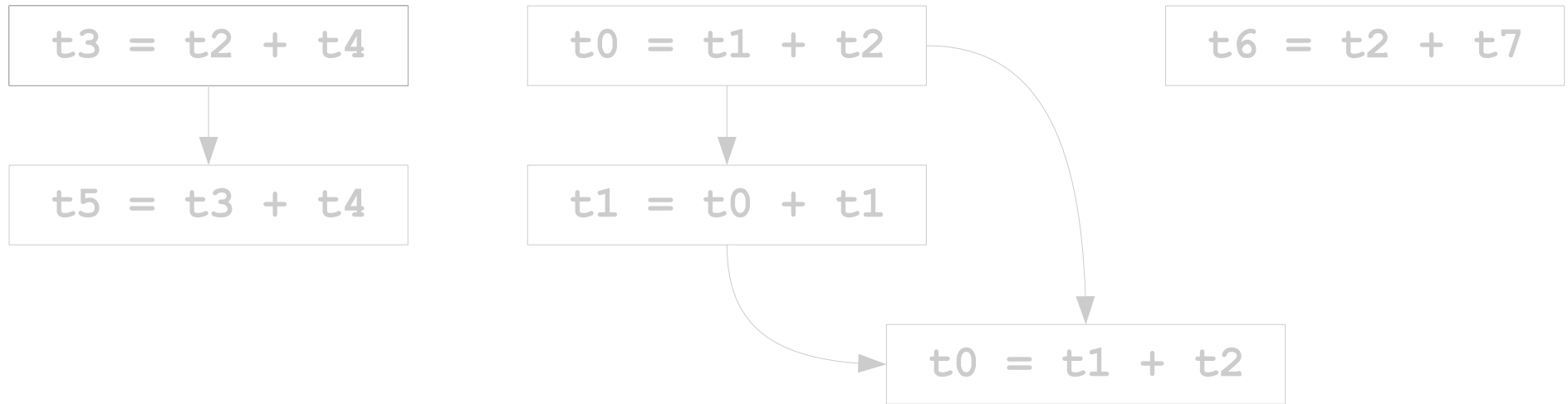
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

Is this a legal
schedule?

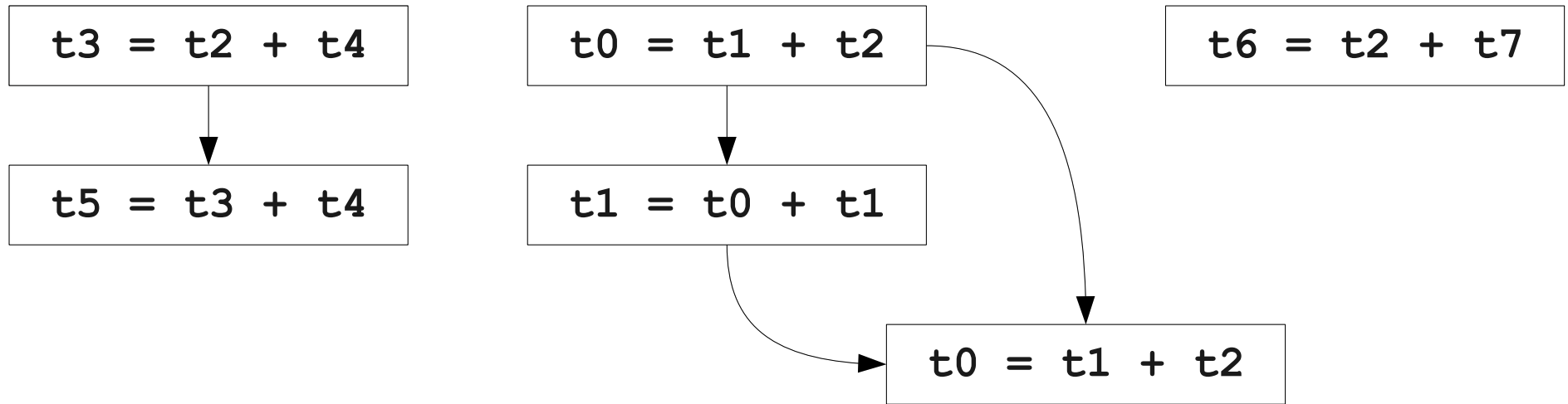
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

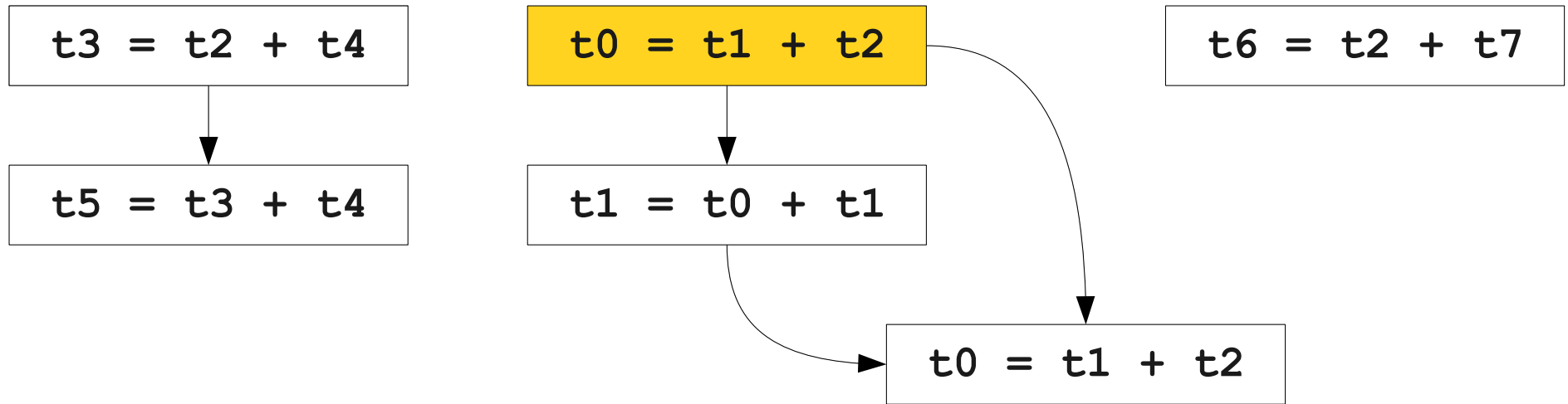
Is this a good
schedule?

Instruction Scheduling



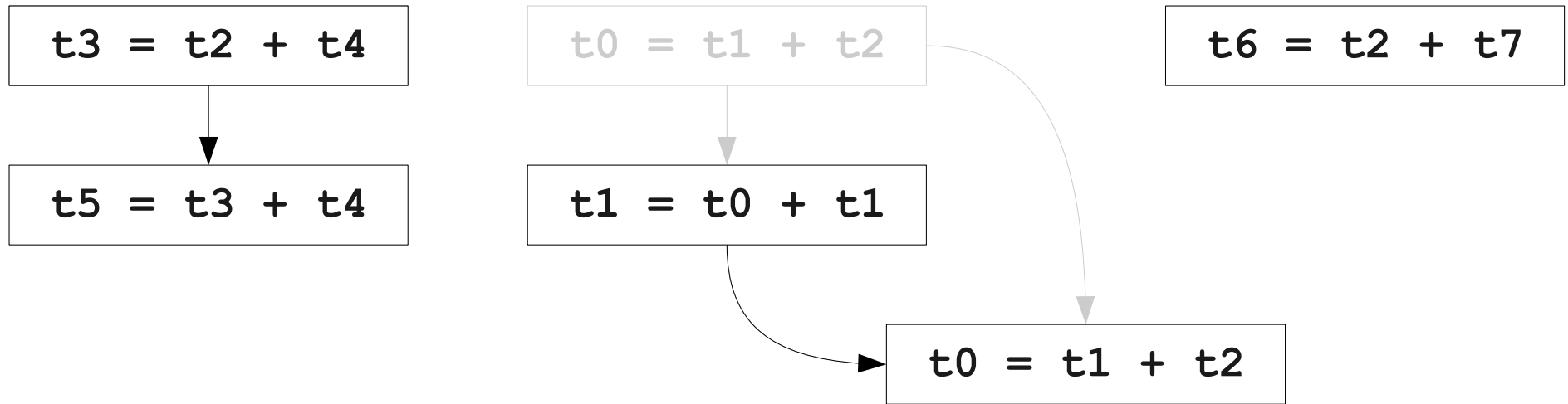
$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

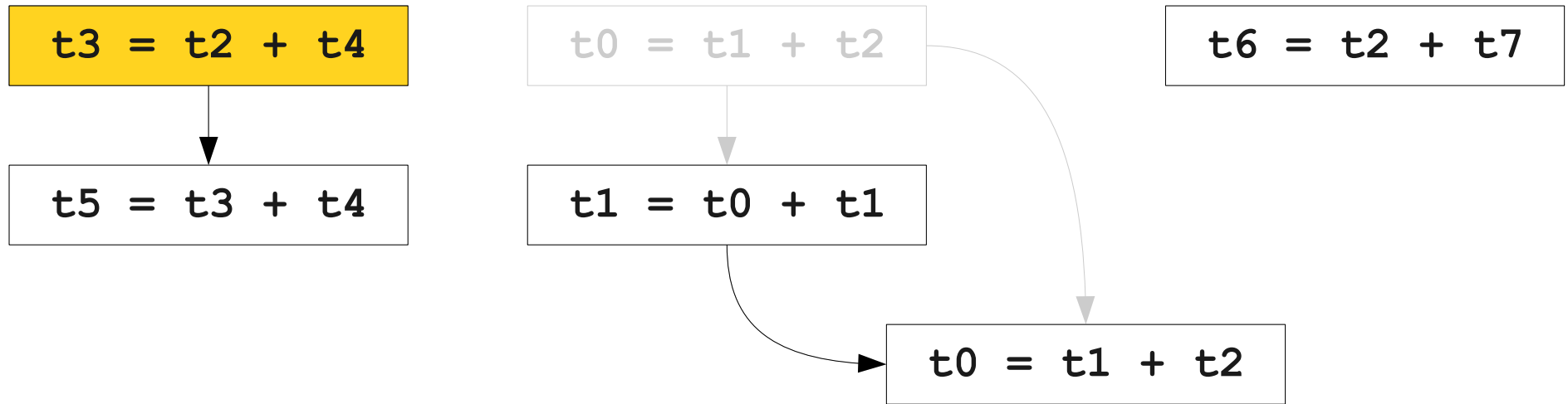
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$

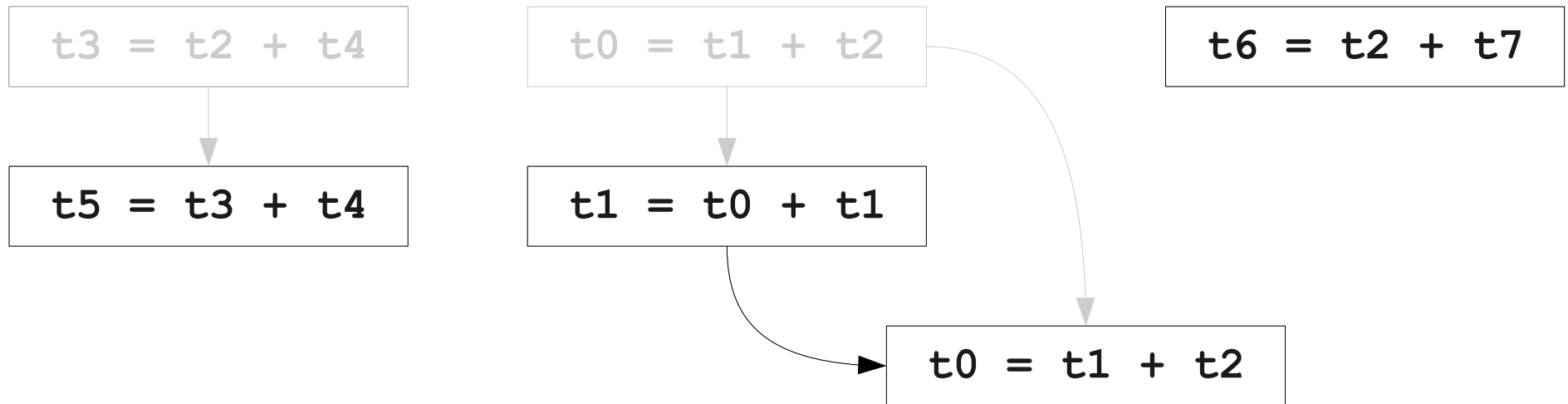
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$

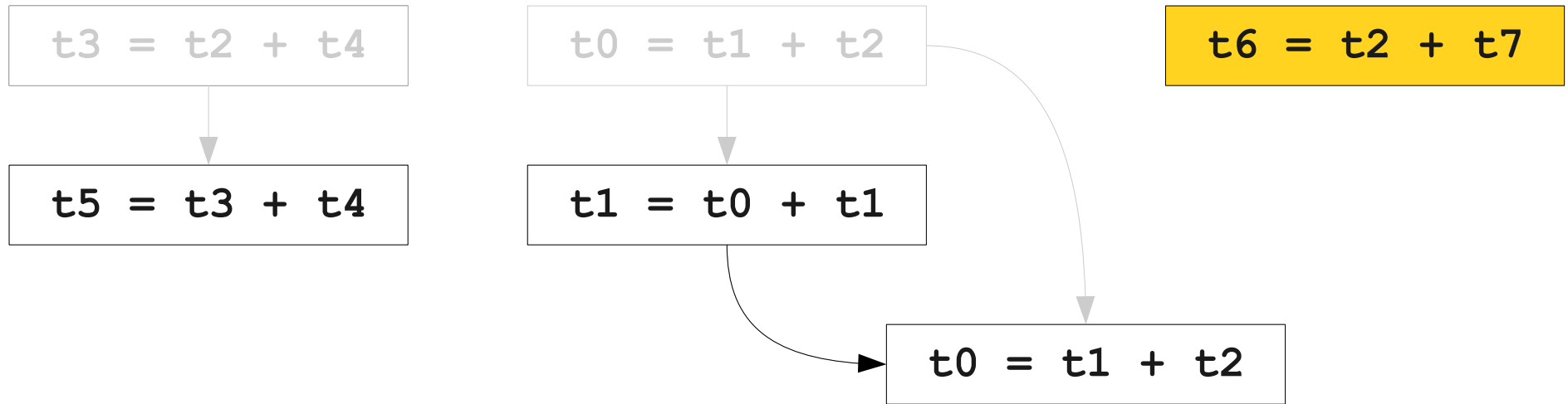
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$

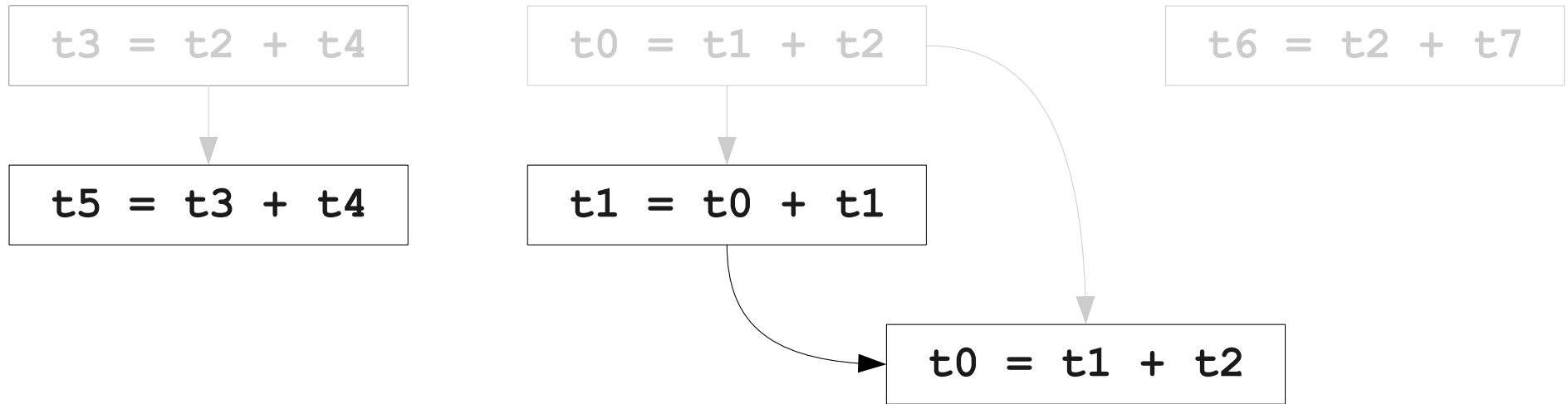
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$

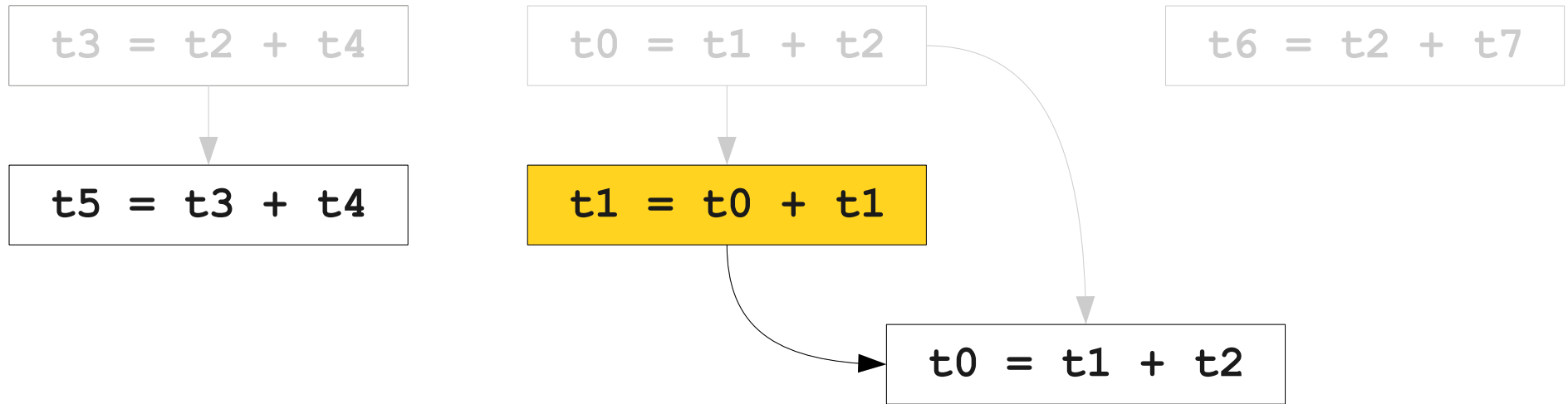
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$

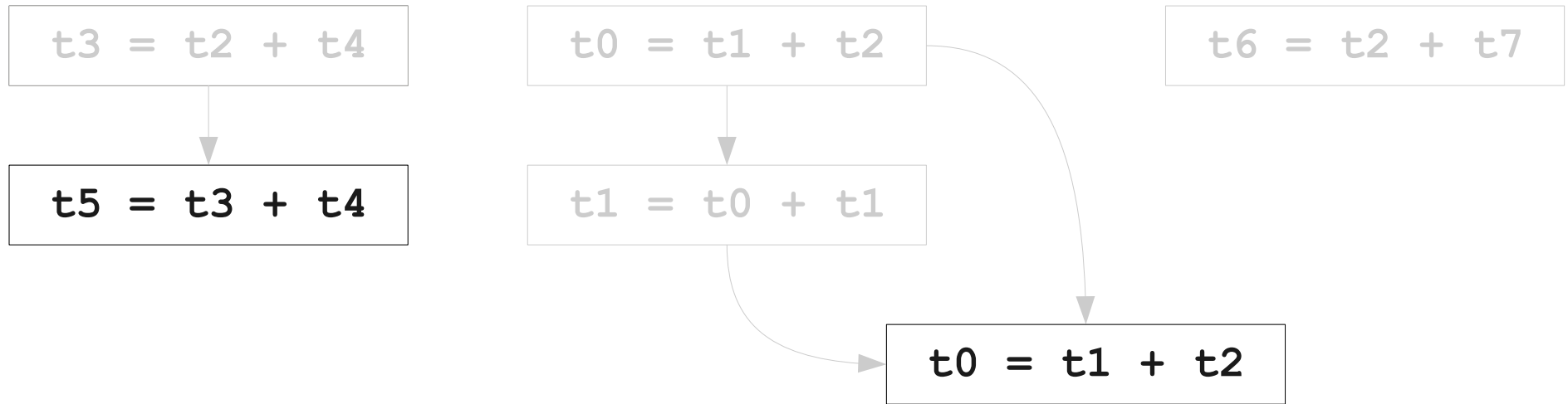
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$

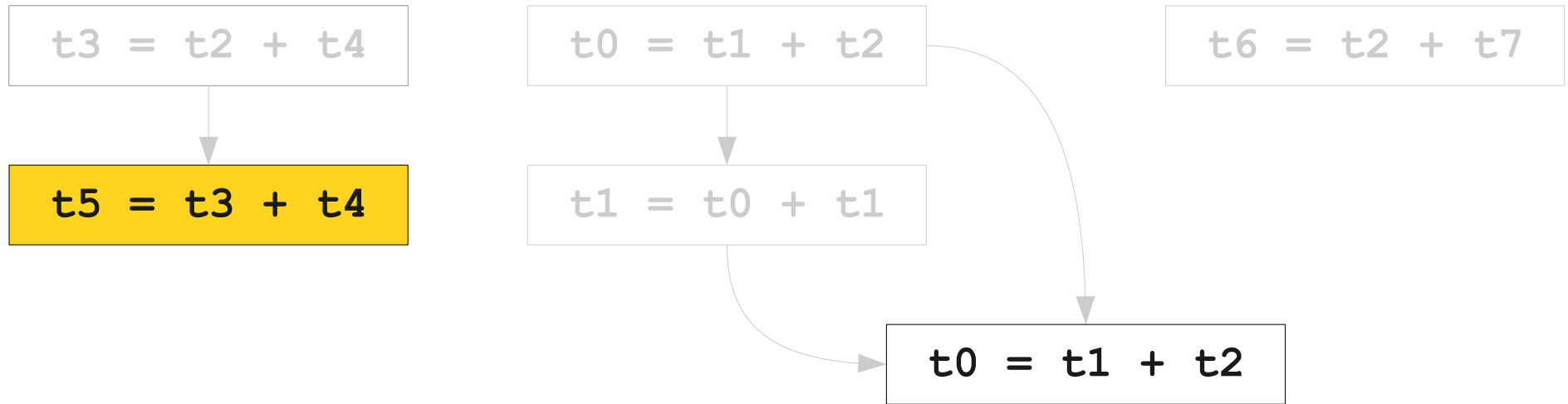
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$
$t1 = t0 + t1$

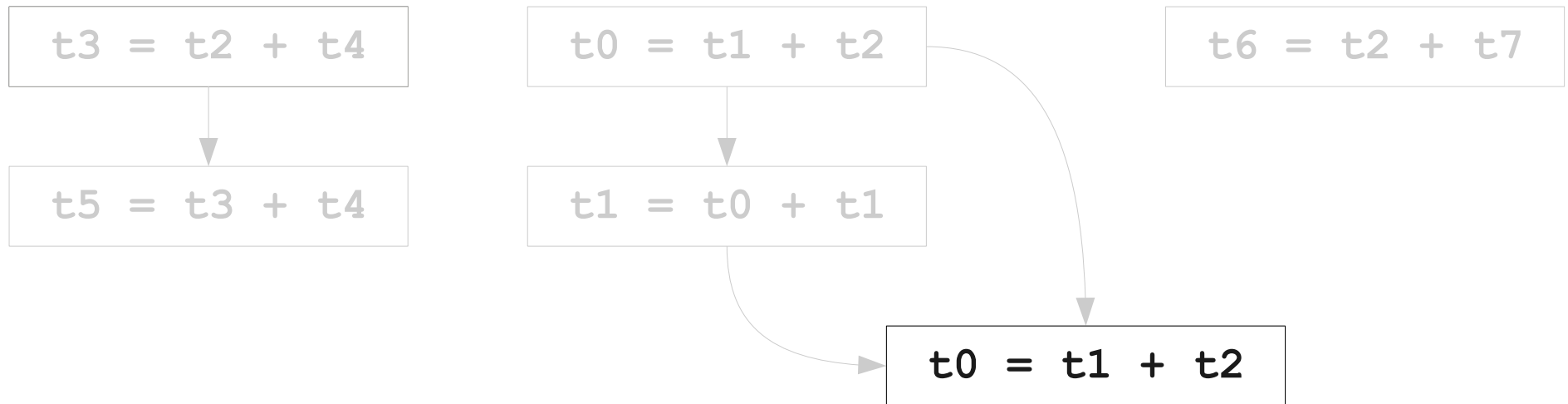
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$
$t1 = t0 + t1$

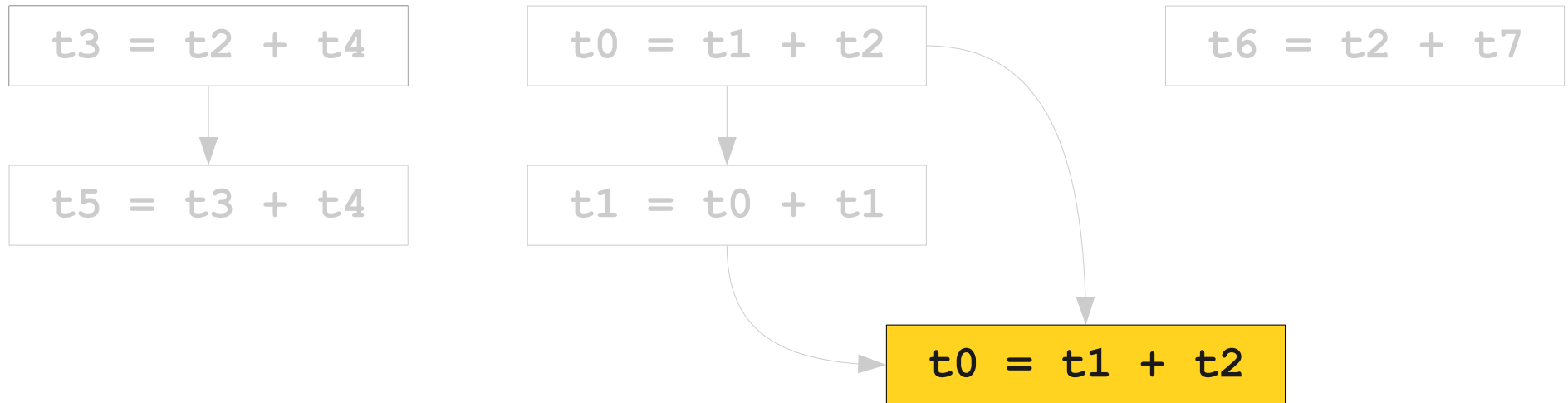
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$
$t1 = t0 + t1$
$t5 = t3 + t4$

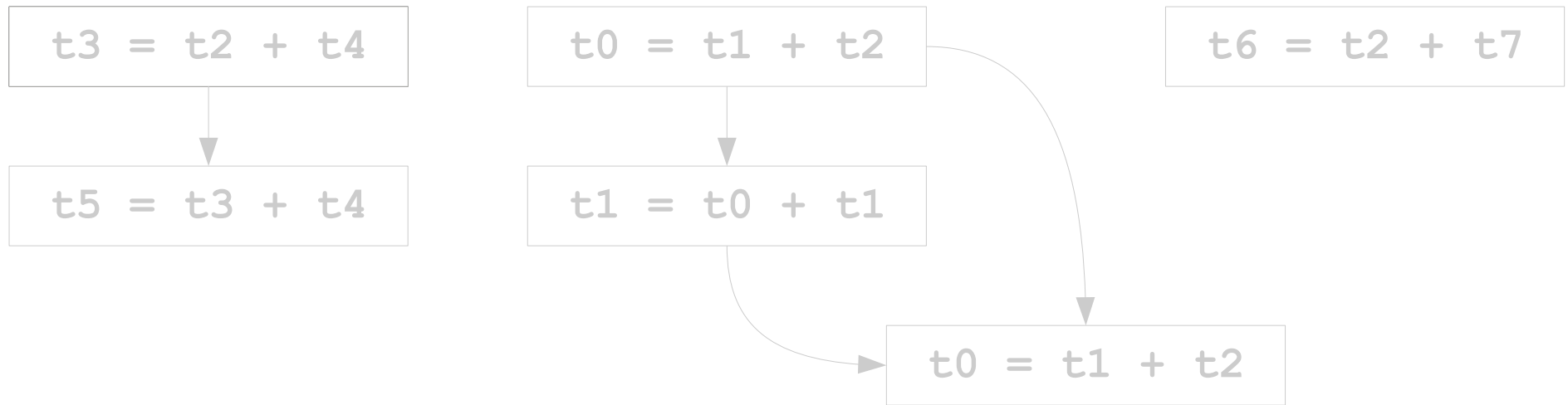
Instruction Scheduling



$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
$t6 = t2 + t7$

$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$
$t1 = t0 + t1$
$t5 = t3 + t4$

Instruction Scheduling



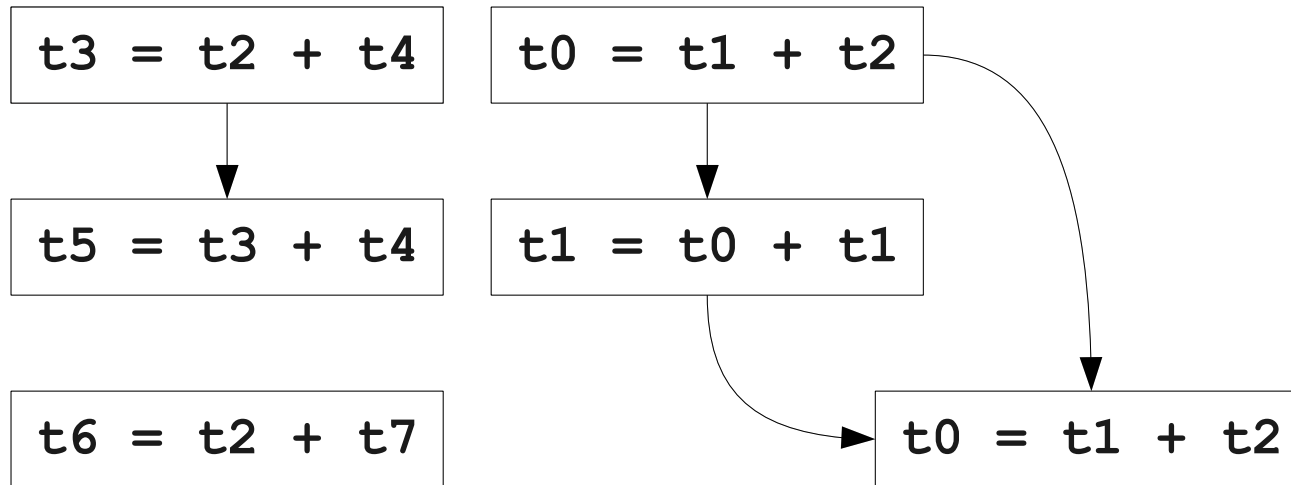
$t3 = t2 + t4$
$t5 = t3 + t4$
$t0 = t1 + t2$
$t1 = t0 + t1$
$t0 = t1 + t2$
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$t0 = t1 + t2$
$t3 = t2 + t4$
$t6 = t2 + t7$
$t1 = t0 + t1$
$t5 = t3 + t4$
$t0 = t1 + t2$

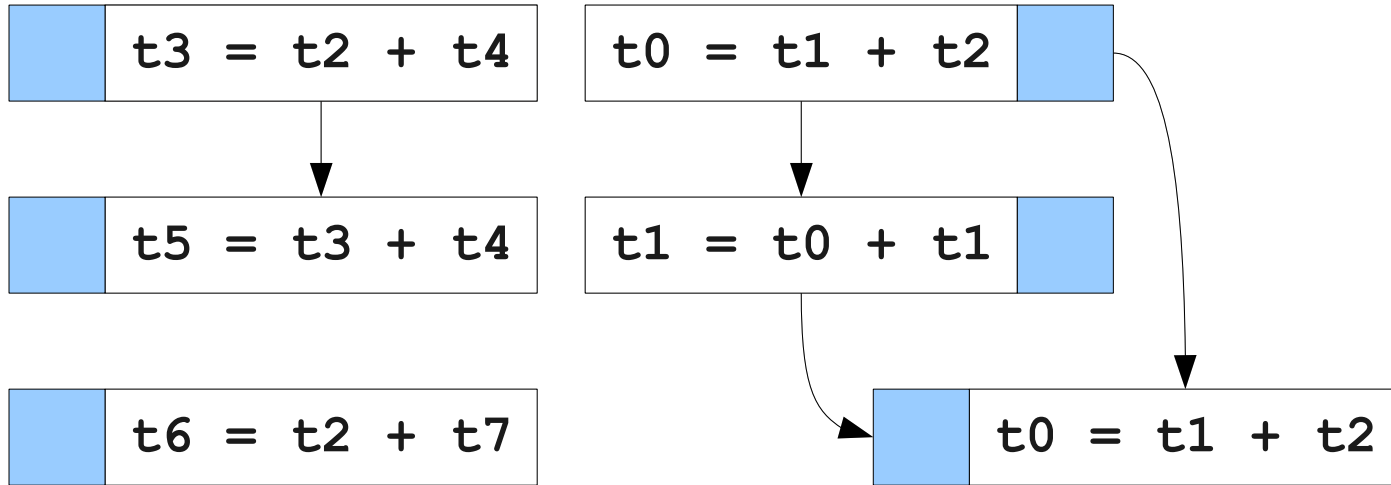
One Small Problem

- There can be many valid topological orderings of a data dependency graph.
- How do we pick one that works well with the pipeline?
- In general, finding the fastest instruction schedule is known to be **NP-hard**.
 - Don't expect a polynomial-time algorithm anytime soon!
- Heuristics are used in practice:
 - Schedule instructions that can run to completion without interference before instructions that cause interference.
 - Schedule instructions with more dependents before instructions with fewer dependents.

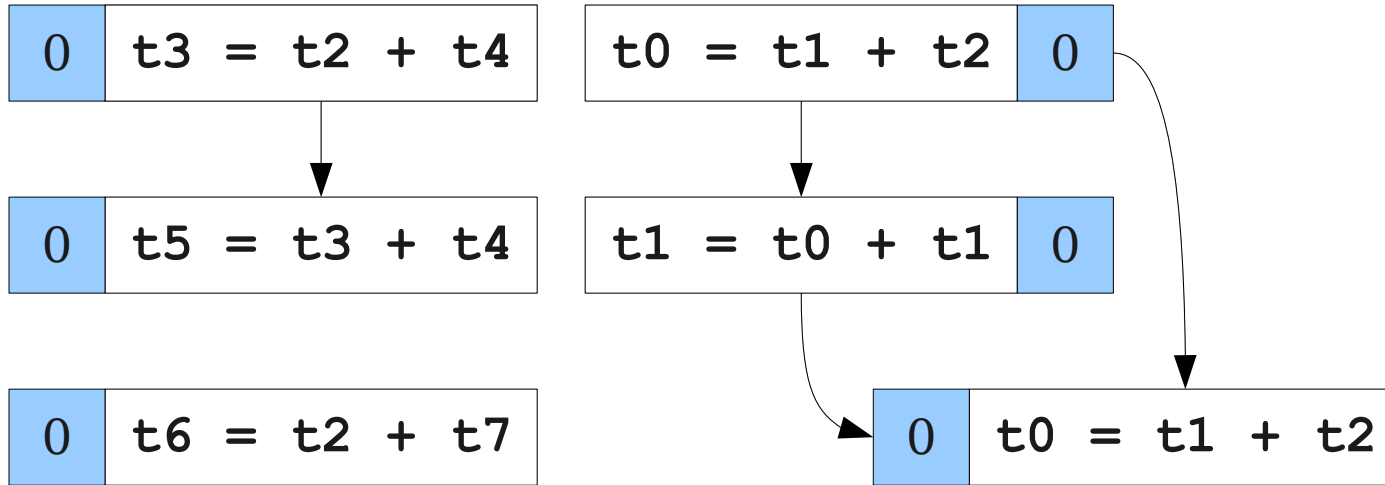
Instruction Scheduling



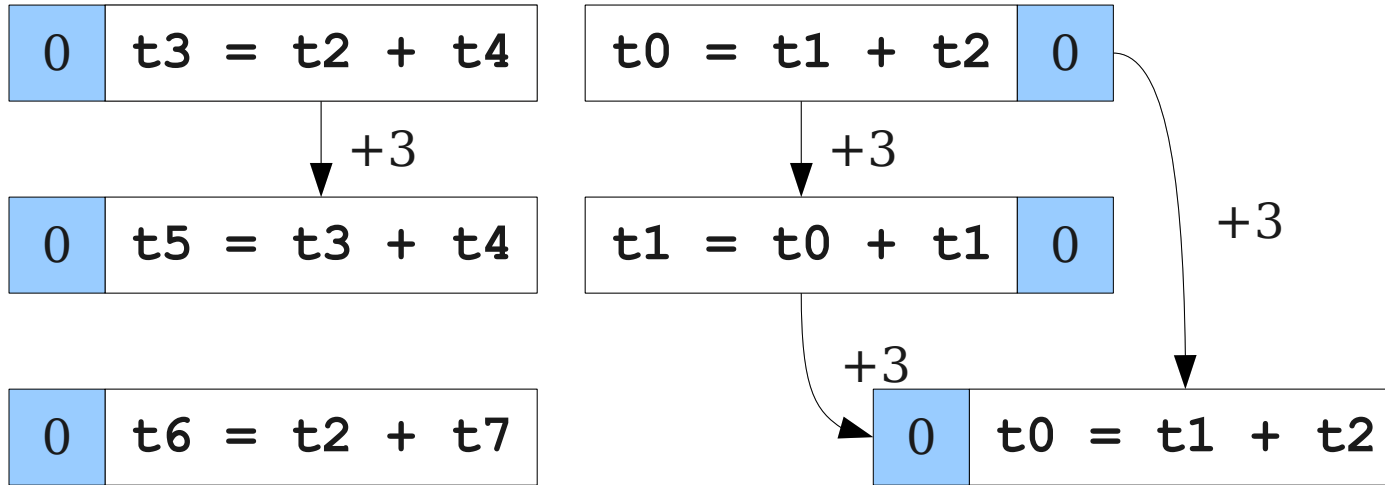
Instruction Scheduling



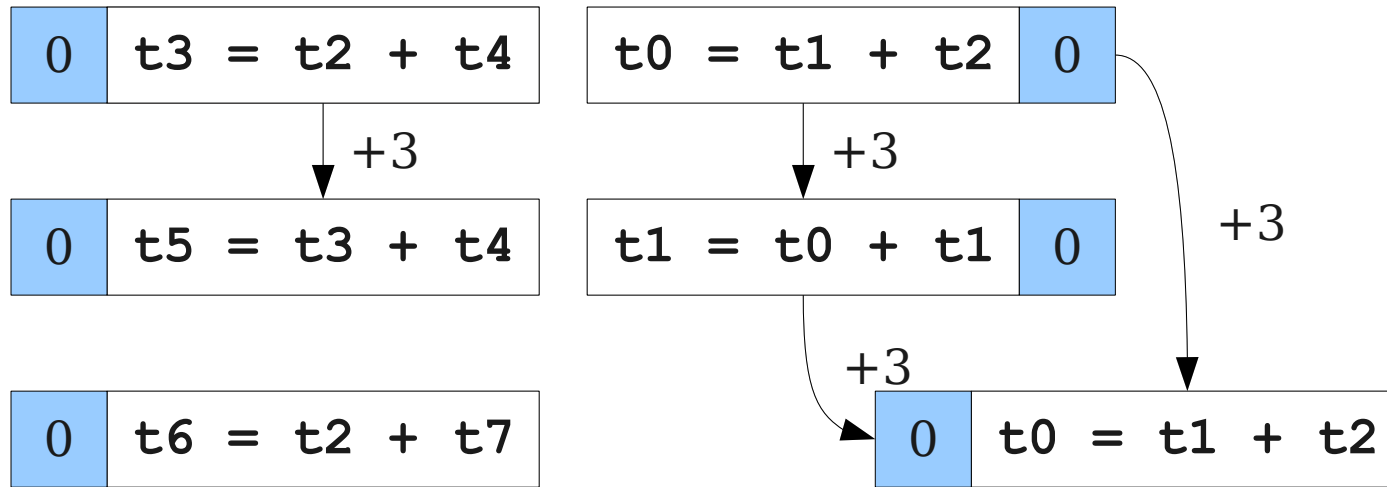
Instruction Scheduling



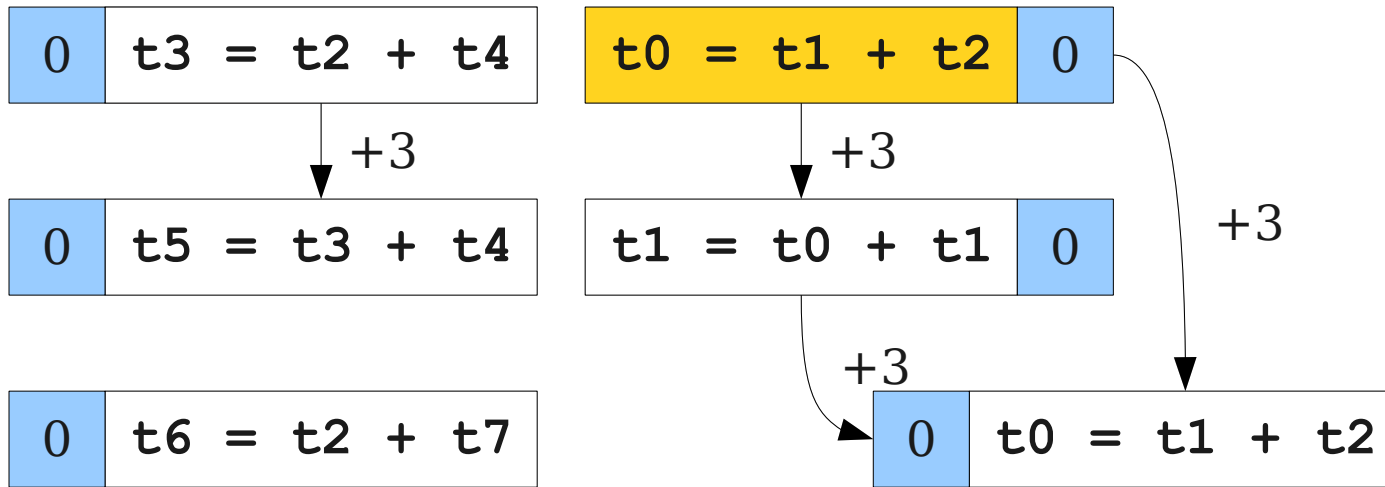
Instruction Scheduling



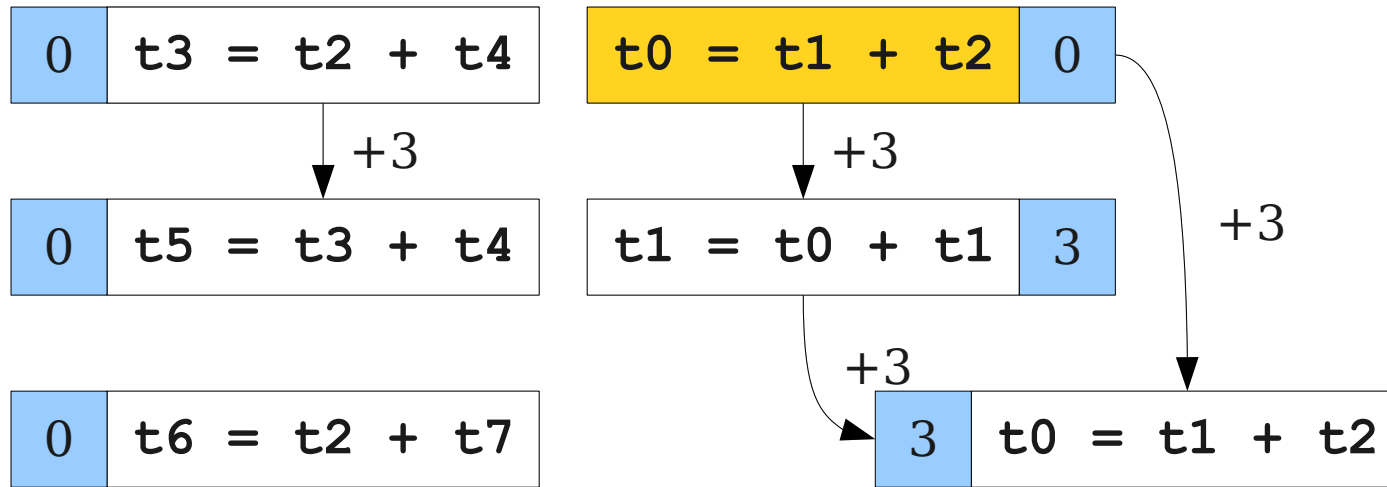
Instruction Scheduling

[illegible]

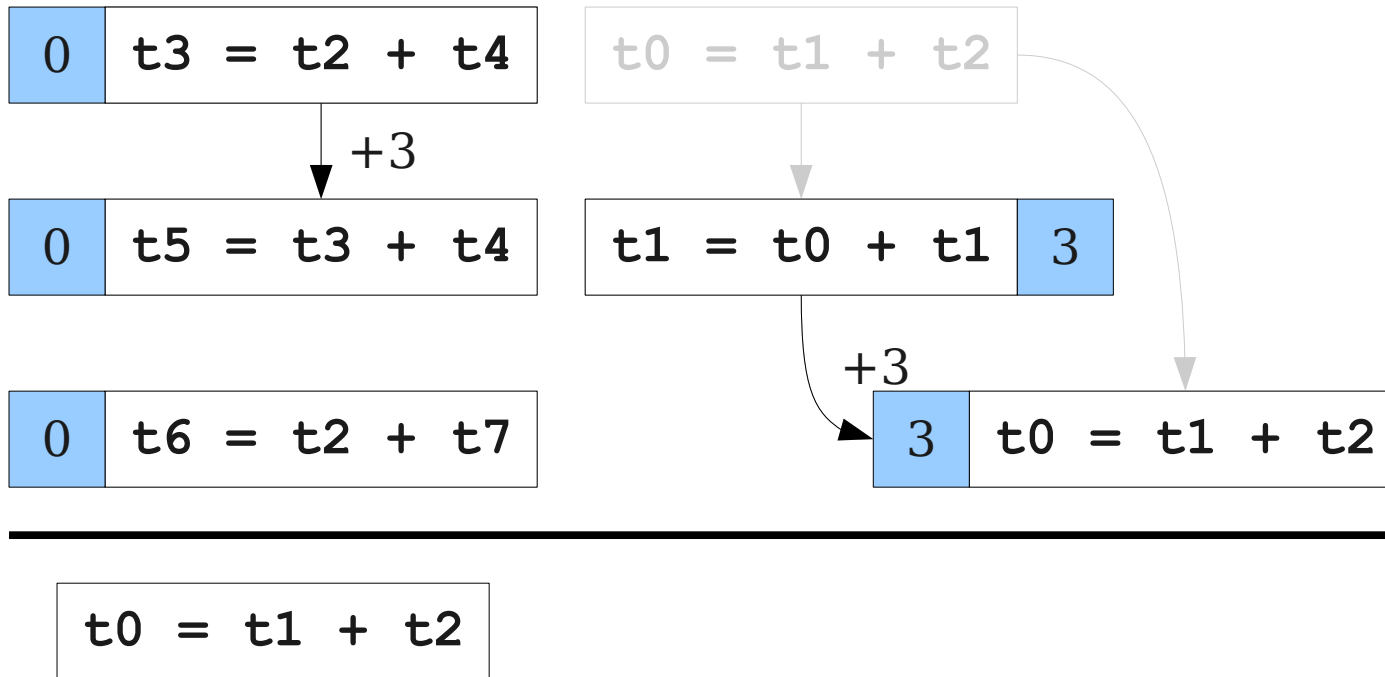
Instruction Scheduling


$$t_0 = t_1 + t_2$$
[illegible]

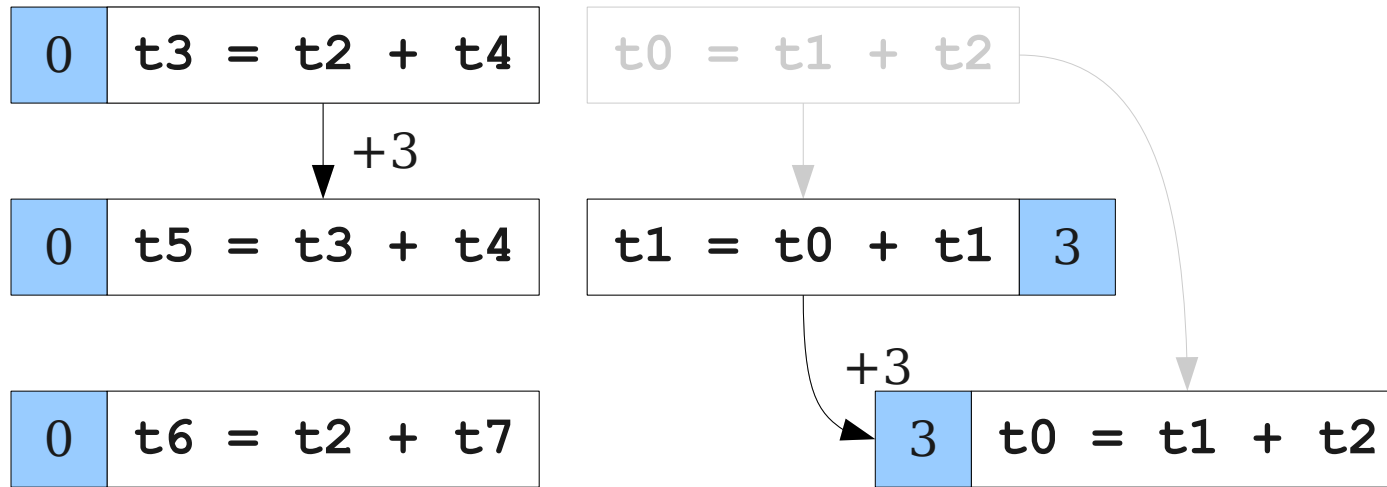
Instruction Scheduling


$$t_0 = t_1 + t_2$$
[illegible]

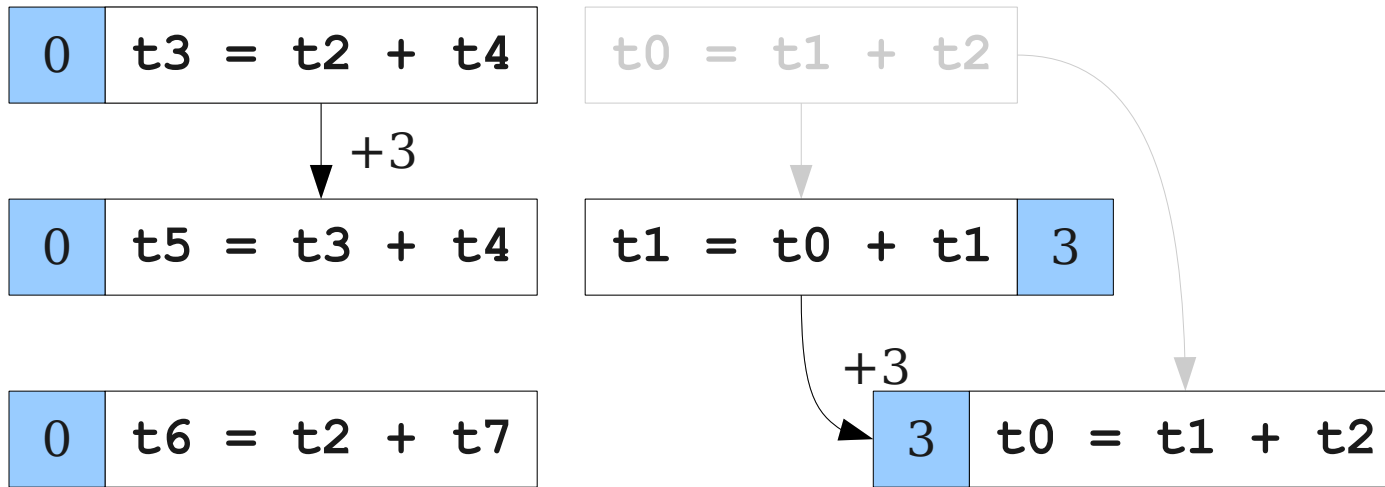
Instruction Scheduling

[illegible]

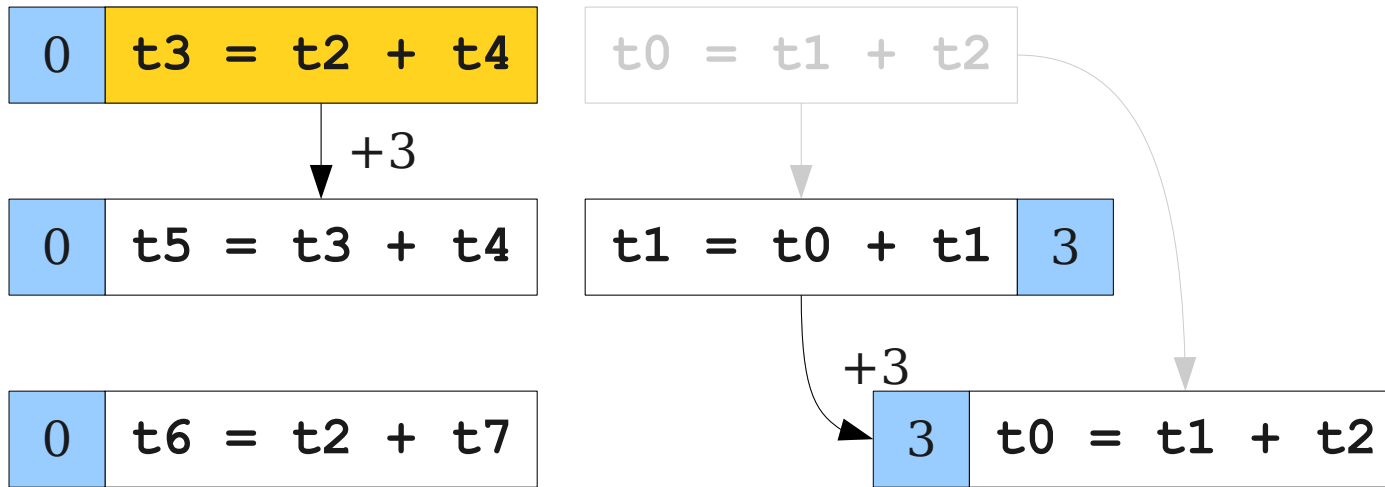
Instruction Scheduling


$$t_0 = t_1 + t_2$$
[illegible]

Instruction Scheduling


$$t_0 = t_1 + t_2$$
[illegible]

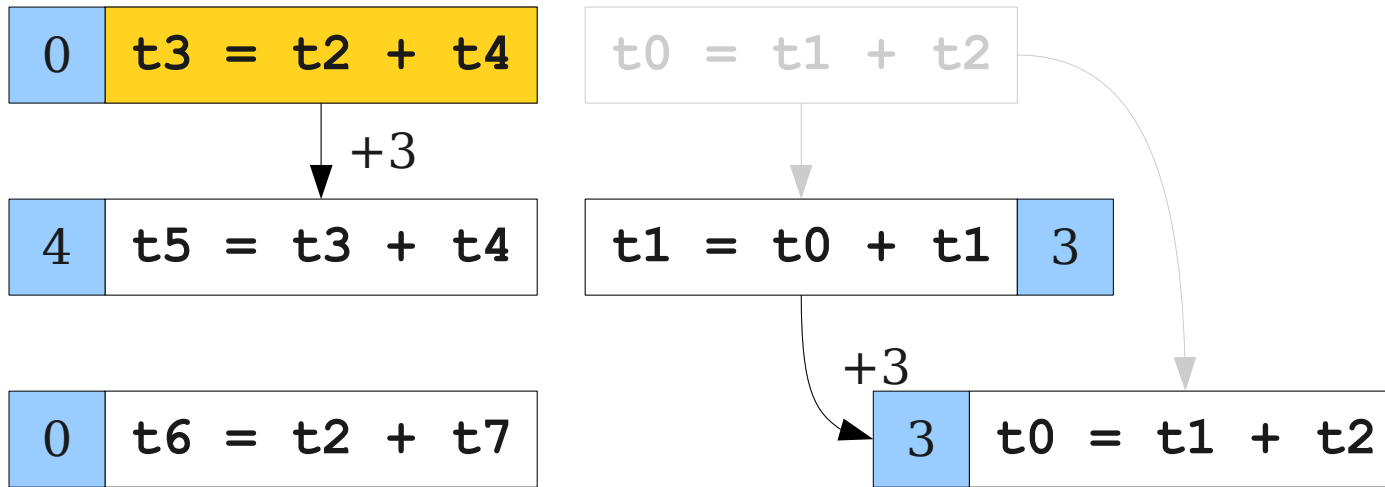
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$

[illegible]

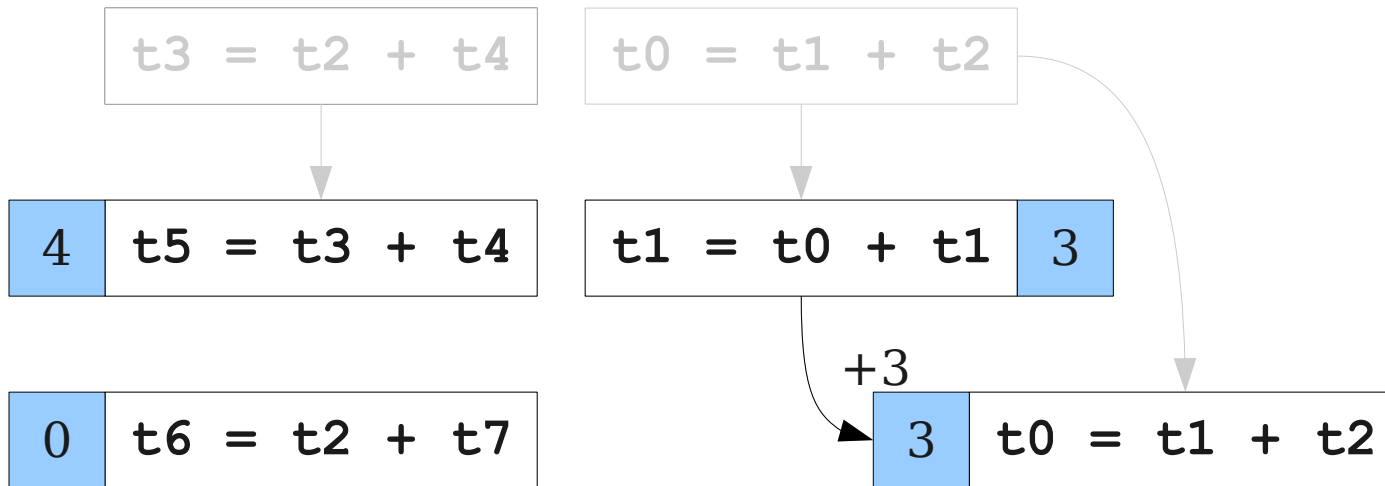
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$

[illegible]

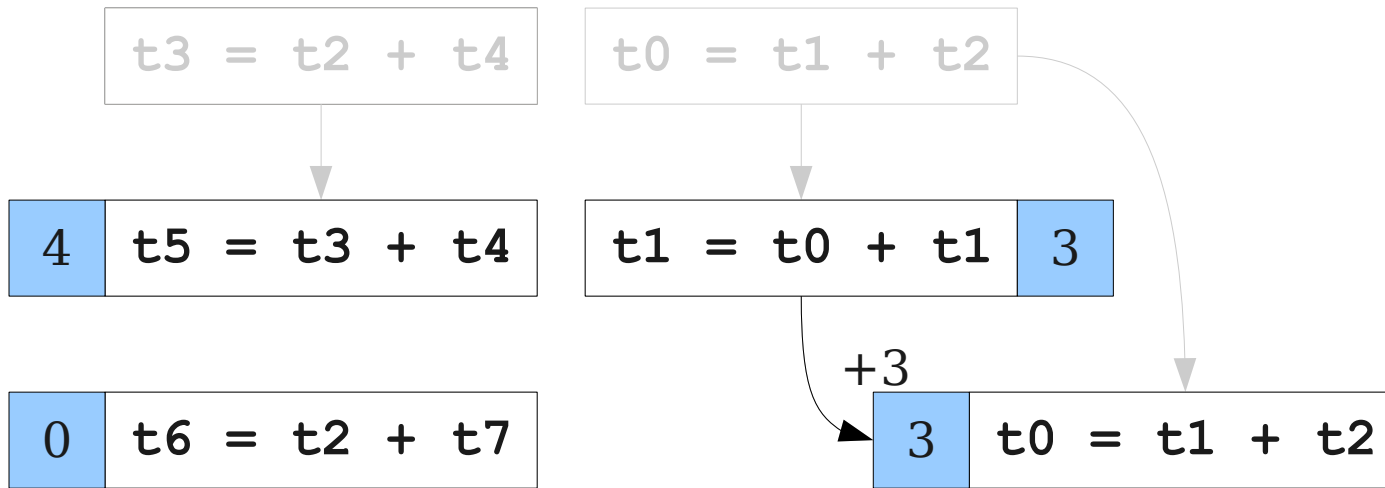
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$

[illegible]

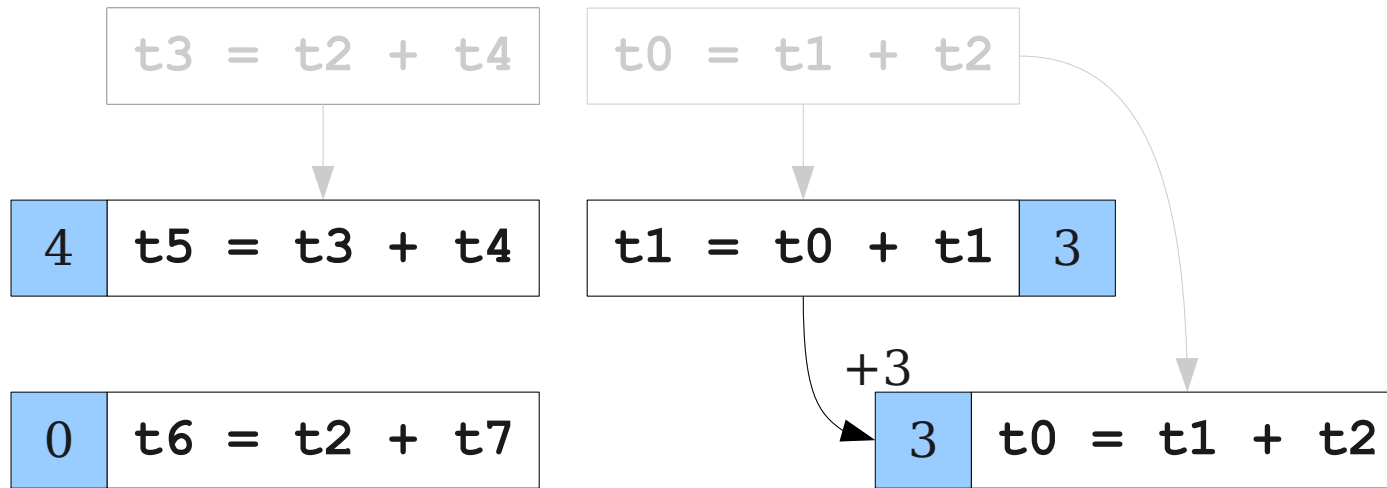
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$

[illegible]

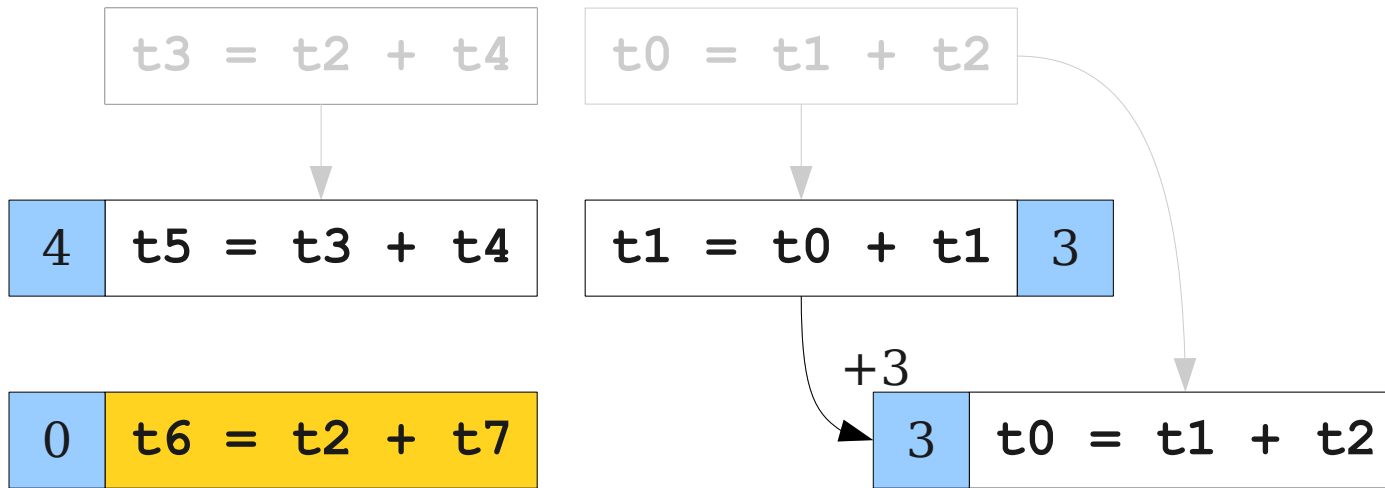
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$

ID	RR	ALU	RW

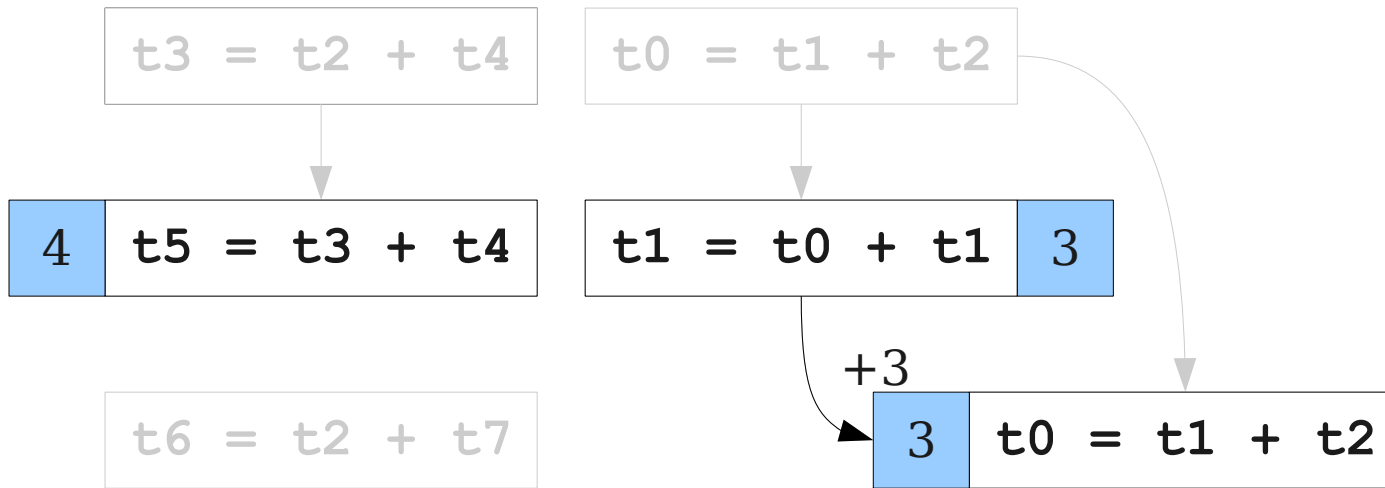
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$

ID	RR	ALU	RW

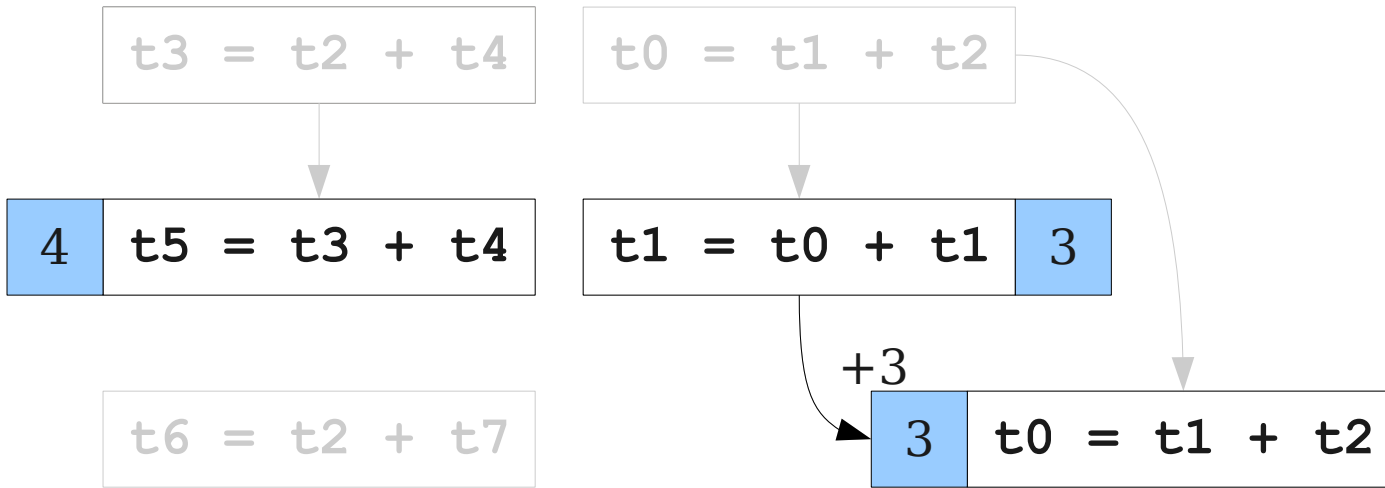
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$

ID	RR	ALU	RW

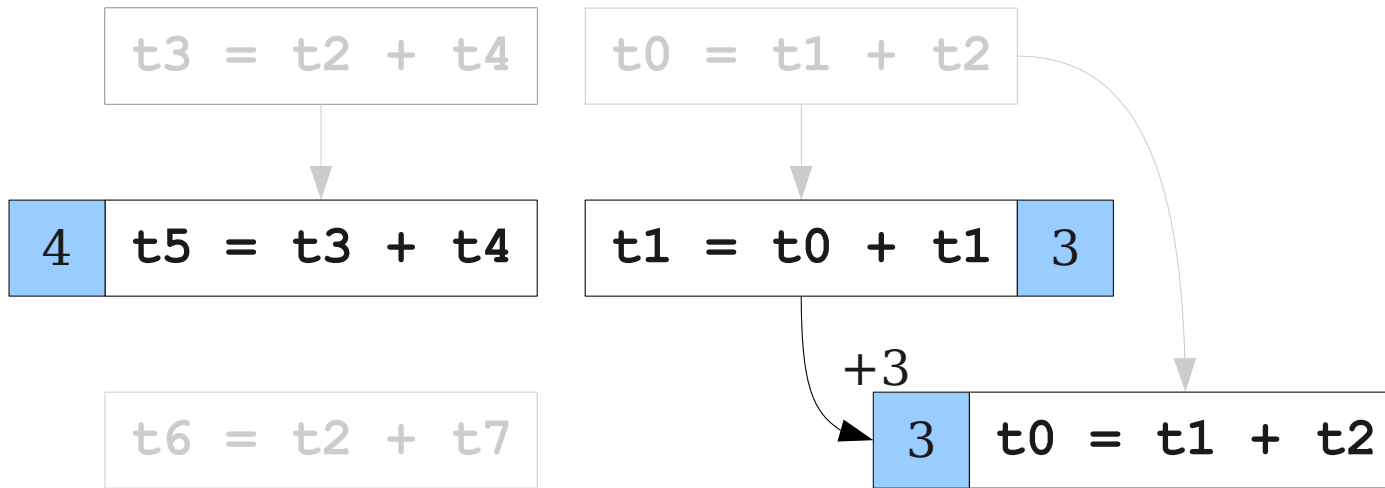
Instruction Scheduling



$t_0 = t_1 + t_2$
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ID	RR	ALU	RW

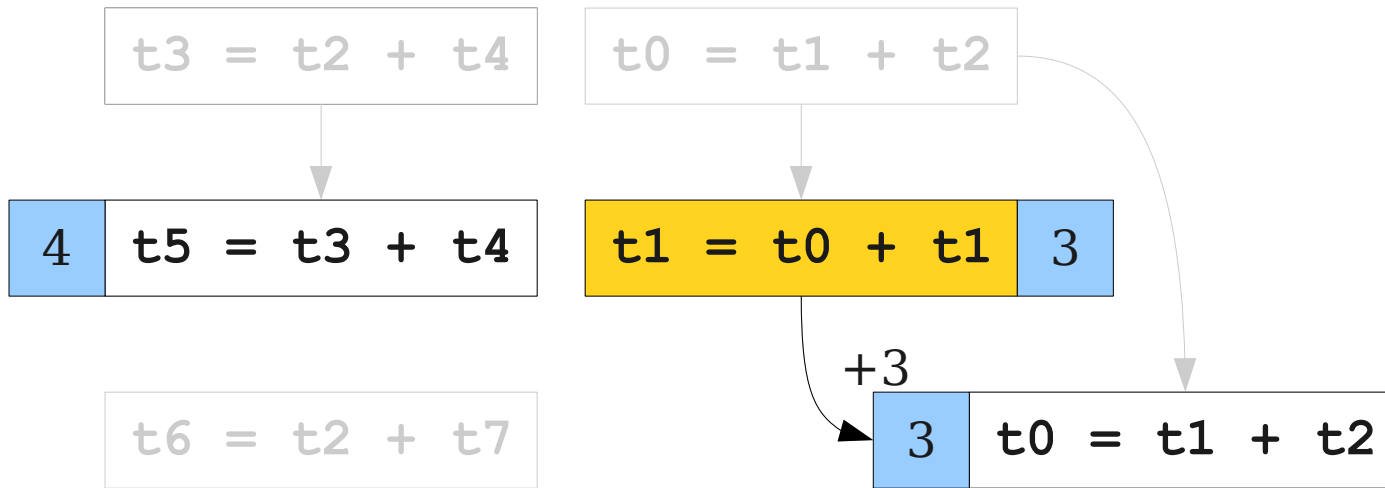
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
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ID	RR	ALU	RW

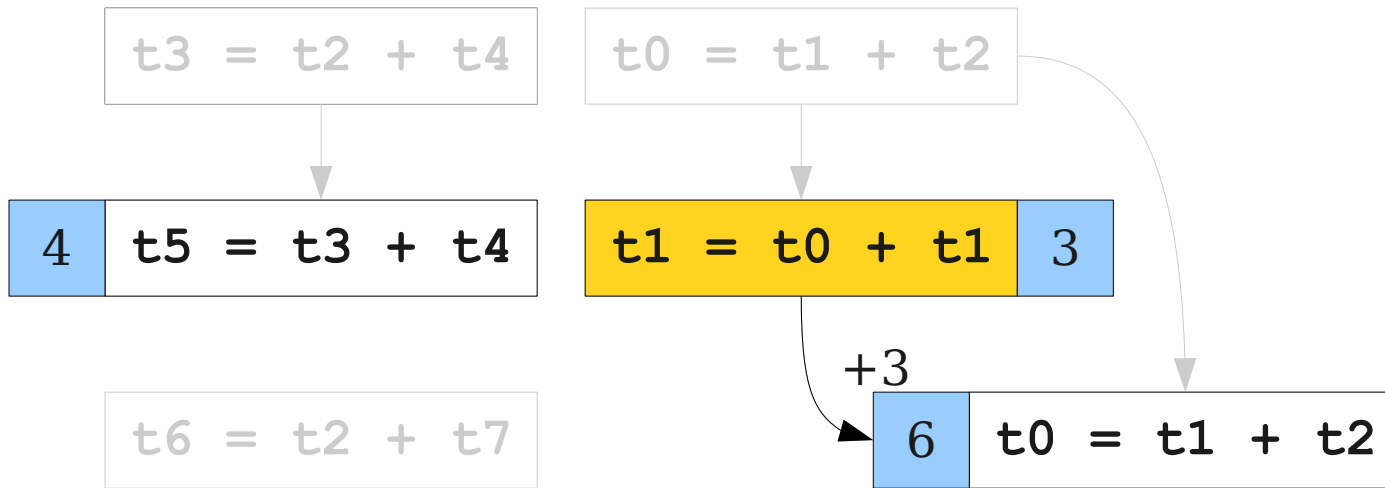
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$

ID	RR	ALU	RW

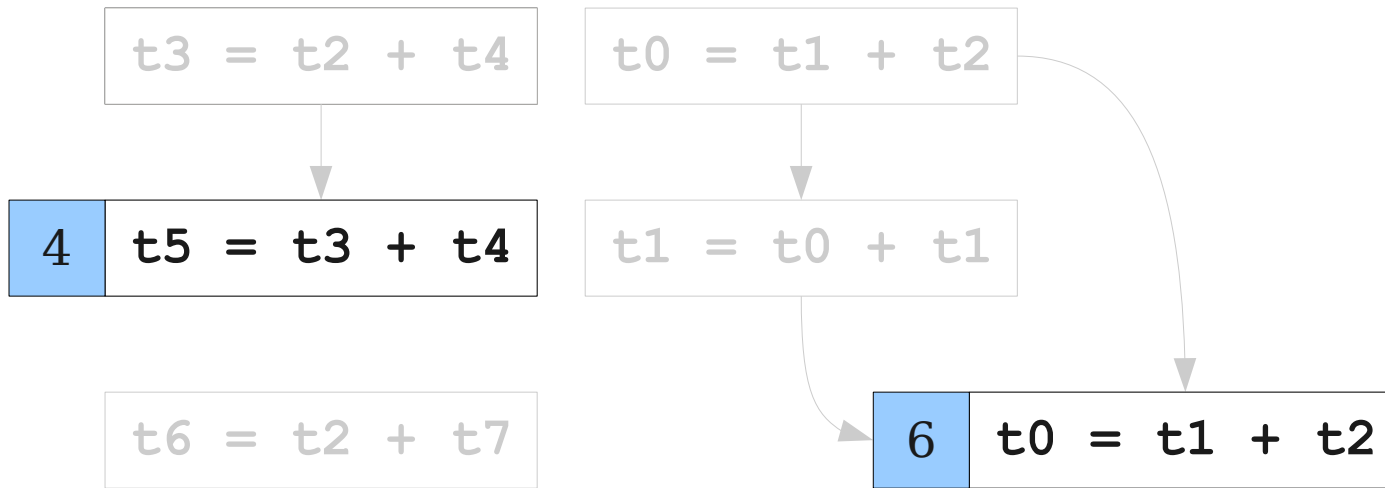
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$

ID	RR	ALU	RW

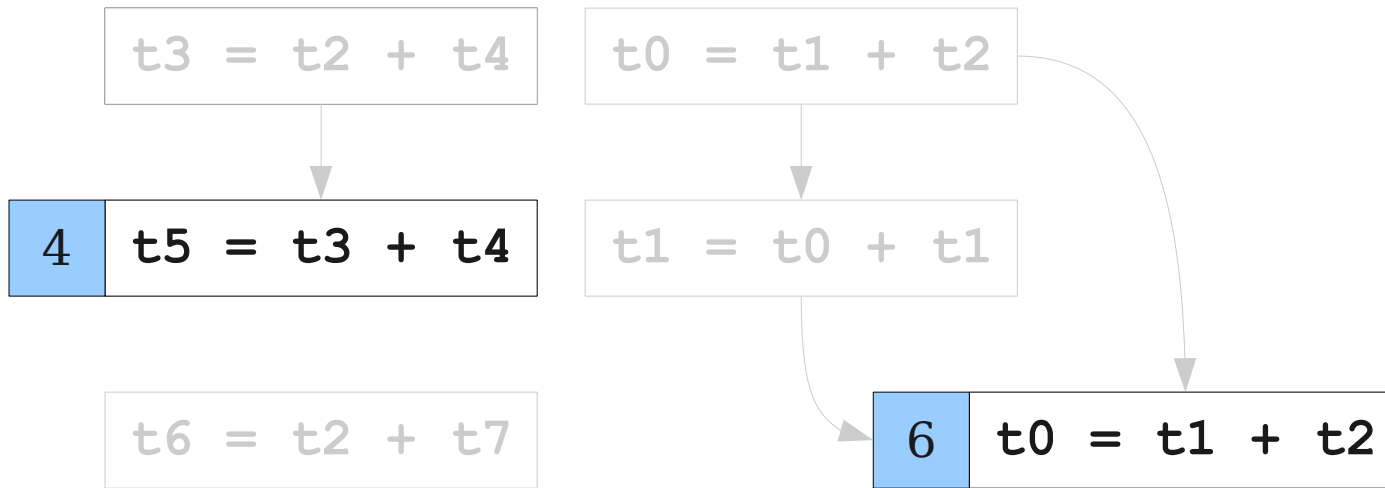
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$

ID	RR	ALU	RW

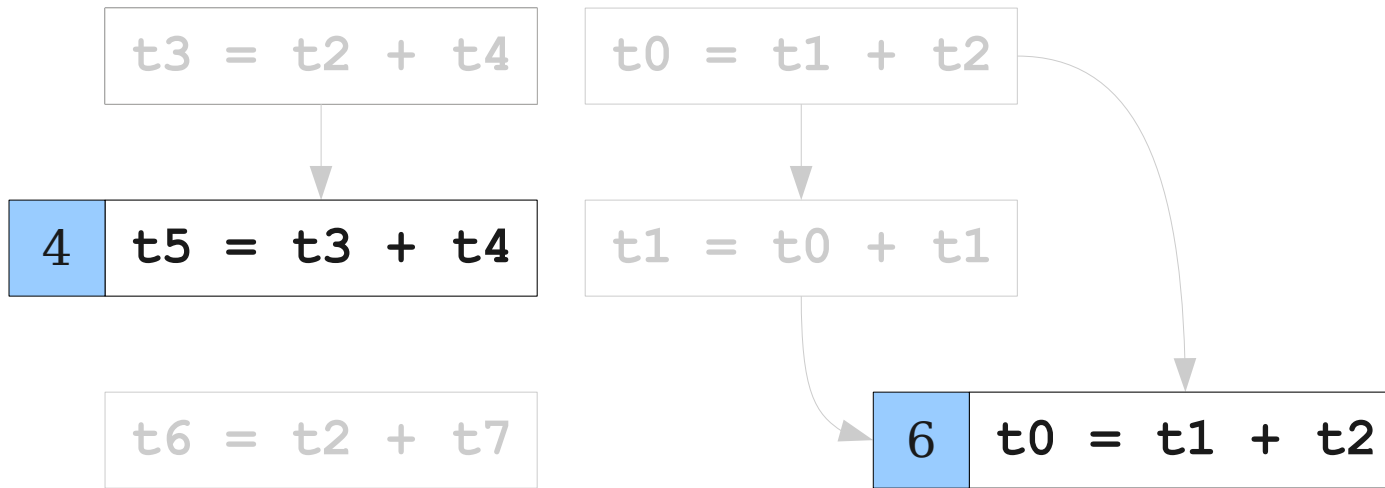
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
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ID	RR	ALU	RW

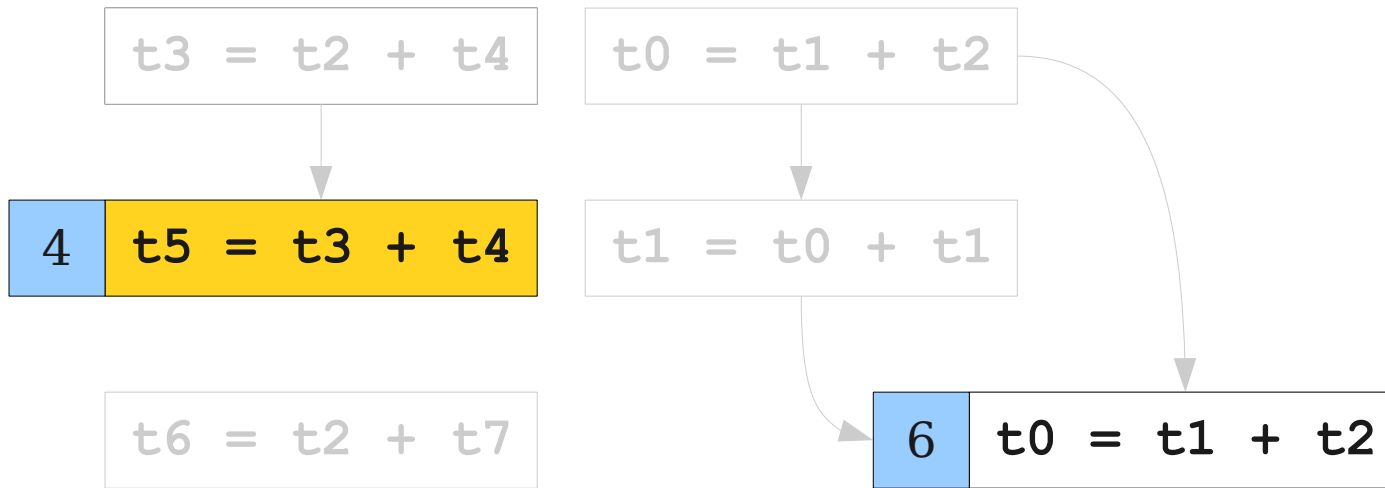
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$

ID	RR	ALU	RW

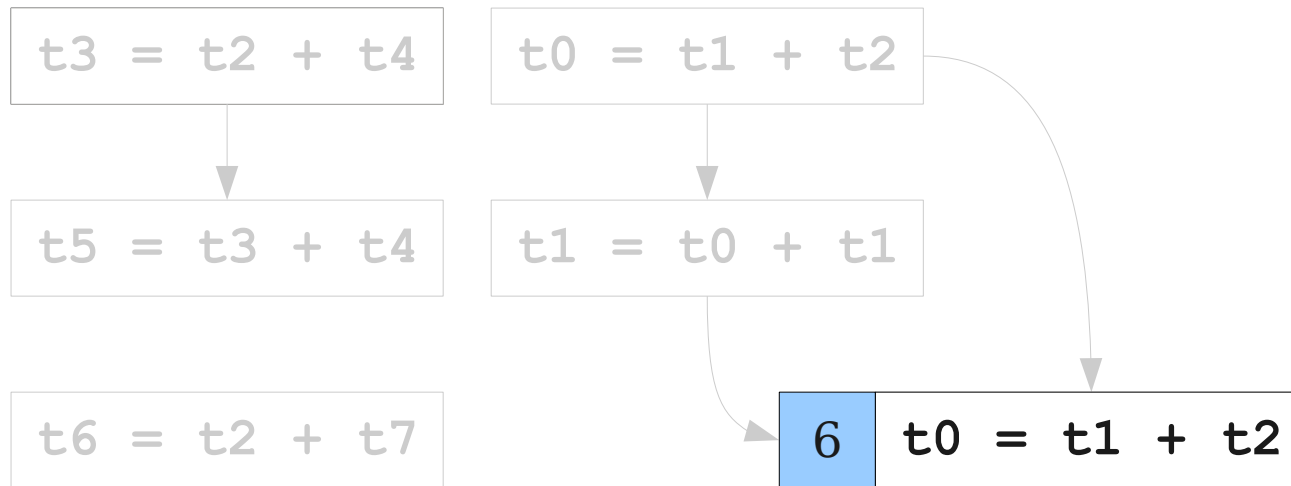
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$
$t_5 = t_3 + t_4$

ID	RR	ALU	RW

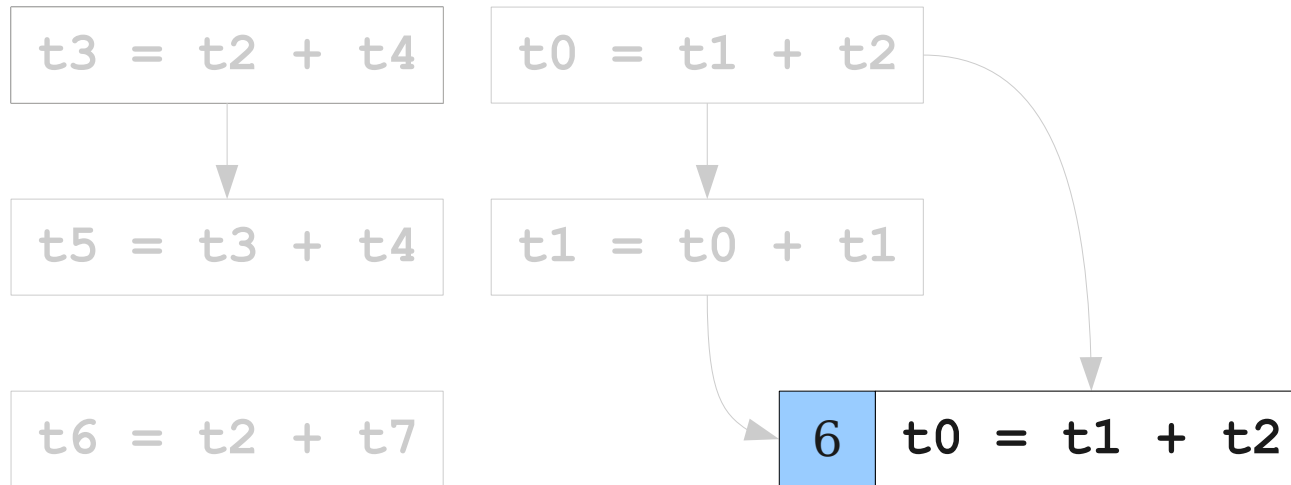
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$
$t_5 = t_3 + t_4$

ID	RR	ALU	RW

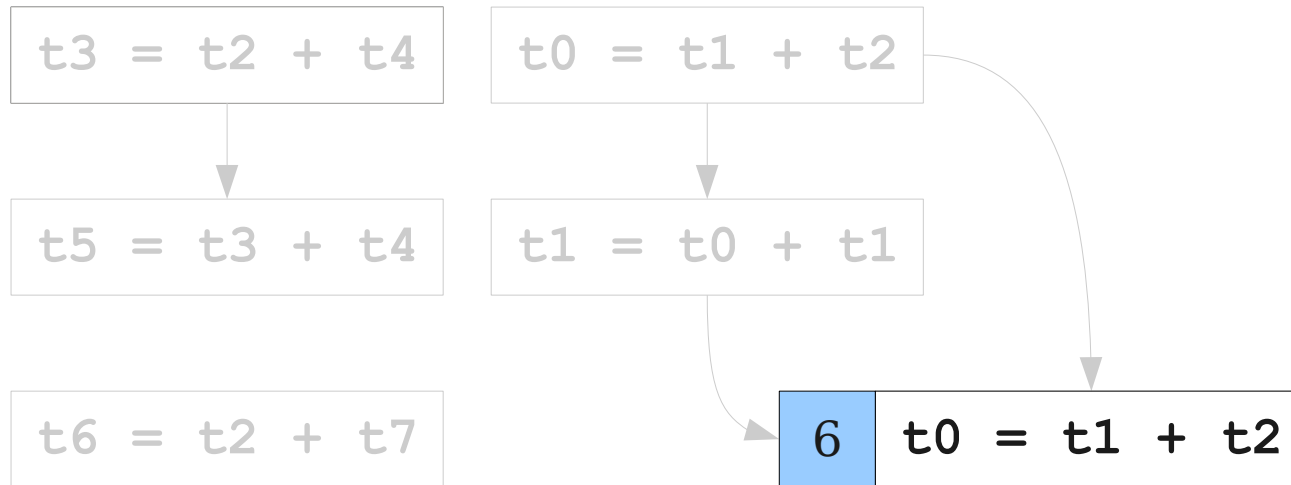
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$
$t_5 = t_3 + t_4$

ID	RR	ALU	RW

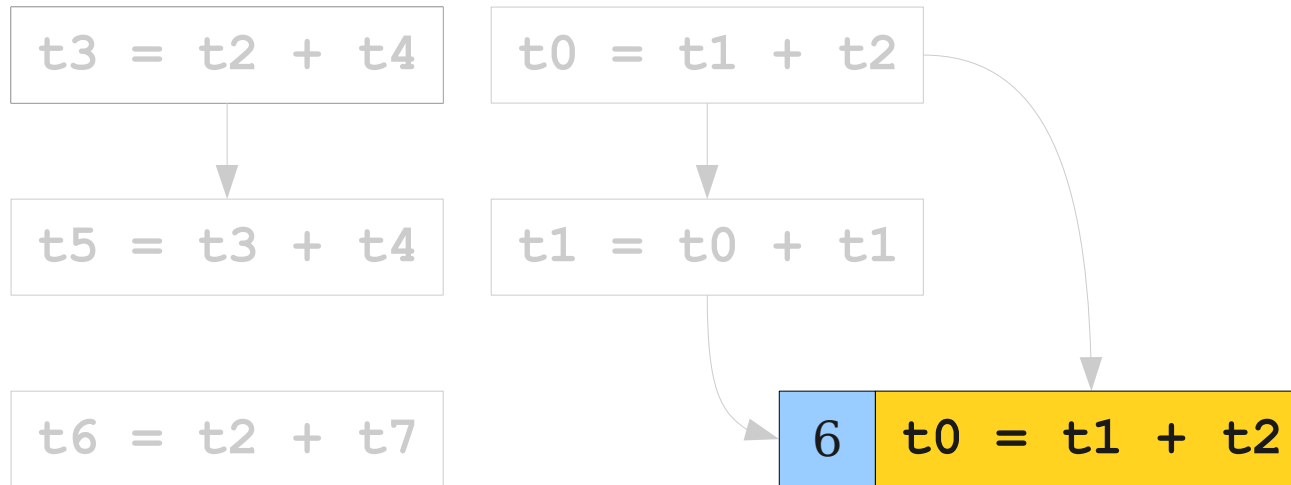
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$
$t_5 = t_3 + t_4$

ID	RR	ALU	RW

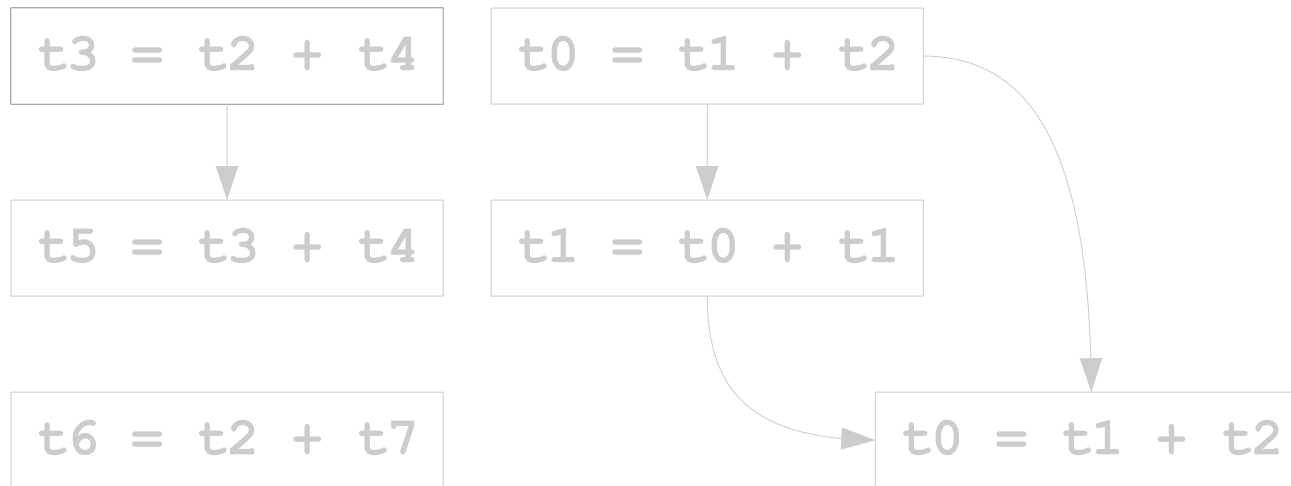
Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$
$t_5 = t_3 + t_4$
$t_0 = t_1 + t_2$

ID	RR	ALU	RW

Instruction Scheduling



$t_0 = t_1 + t_2$
$t_3 = t_2 + t_4$
$t_6 = t_2 + t_7$
$t_1 = t_0 + t_1$
$t_5 = t_3 + t_4$
$t_0 = t_1 + t_2$

[illegible]

Instruction Scheduling

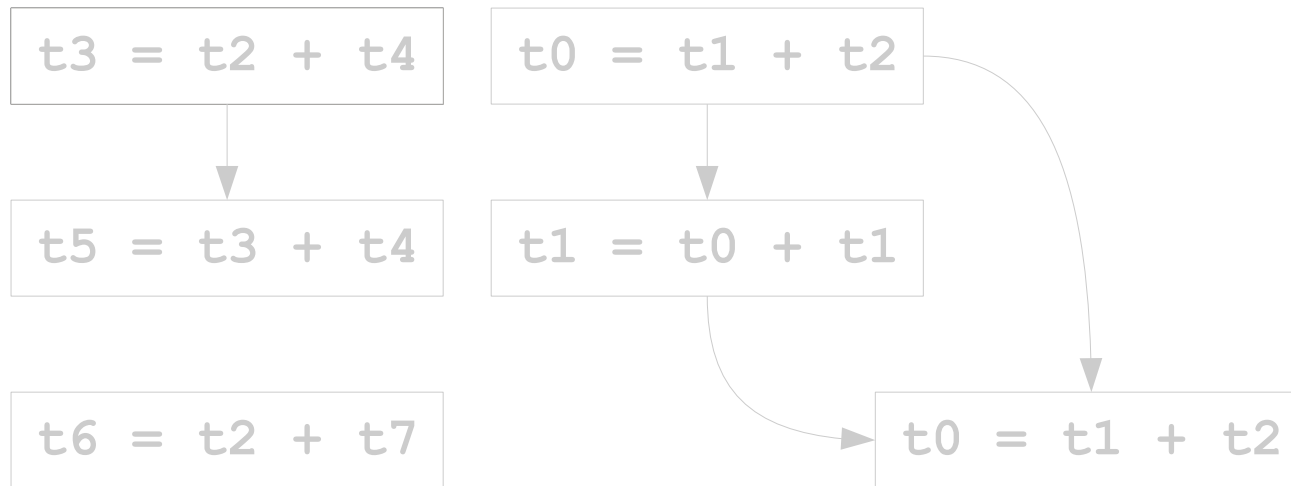


Diagram illustrating a sequence of equations, each on a different colored background:

- $t_0 = t_1 + t_2$ (Magenta background)
- $t_3 = t_2 + t_4$ (Yellow background)
- $t_6 = t_2 + t_7$ (Cyan background)
- $t_1 = t_0 + t_1$ (Red background)
- $t_5 = t_3 + t_4$ (Blue background)
- $t_0 = t_1 + t_2$ (Green background)

ID	RR	ALU	RW

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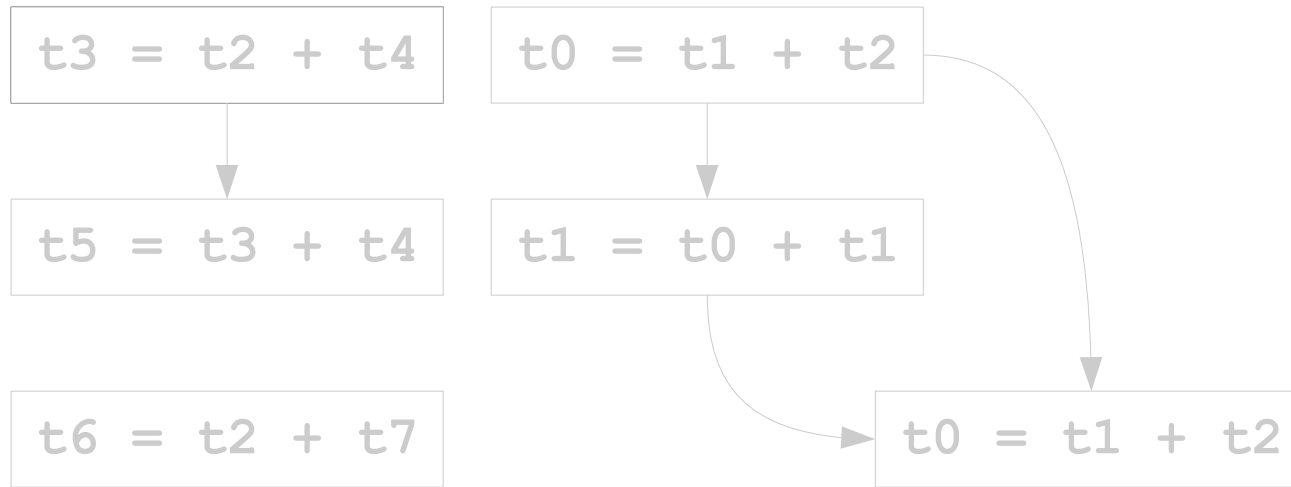


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For Comparison

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More Advanced Scheduling

- Modern optimizing compilers can do far more aggressive scheduling to obtain impressive performance gains.
- One powerful technique: **Loop unrolling**
 - Expand out several loop iterations at once.
 - Use previous algorithm to schedule instructions more intelligently.
 - Can find pipelining-level parallelism across loop iterations.
- Even more powerful technique: **Software pipelining**
 - Loop unrolling on steroids; can convert loops using tens of cycles into loops averaging two or three cycles.

Optimizations for Locality

Memory Caches

- Because computers use different types of memory, there are a variety of memory caches in the machine.
- Caches are designed to anticipate common use patterns.
- Compilers often have to rewrite code to take maximal advantage of these designs.

Locality

- Empirically, many programs exhibit **temporal locality** and **spatial locality**.
- Temporal locality: Memory read recently is likely to be read again.
- Spatial locality: Memory read recently will likely have nearby objects read as well.
- Most memory caches are designed to exploit temporal and spatial locality by
 - Holding recently-used memory addresses in cache.
 - Loading nearby memory addresses into cache.

Memory Caches

Memory Caches

```
arr[0]    = 5;  
arr[2]    = 6;  
arr[10]   = 13;  
arr[1]    = 4;
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Already in
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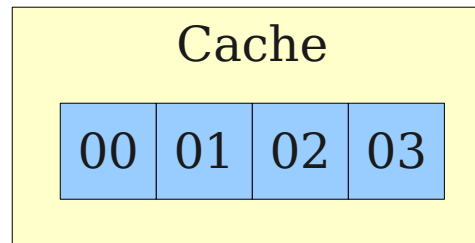
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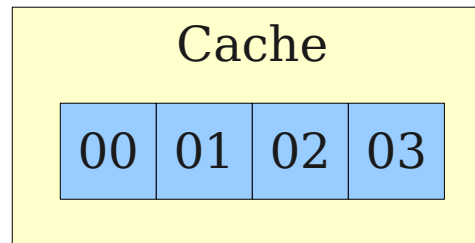
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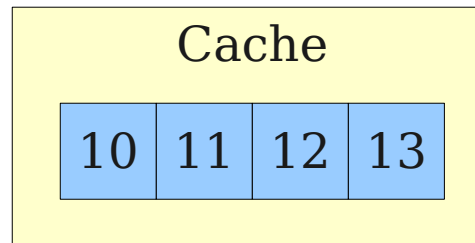
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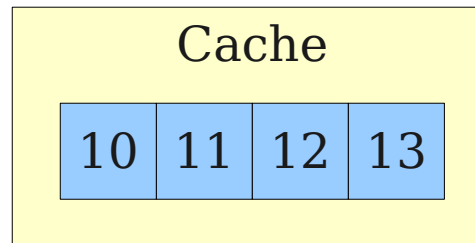
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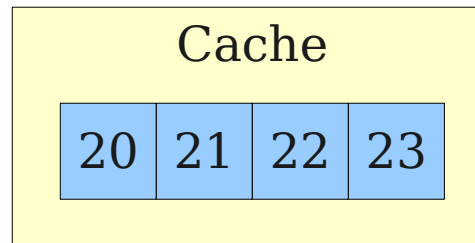
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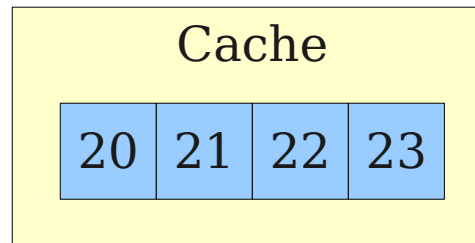
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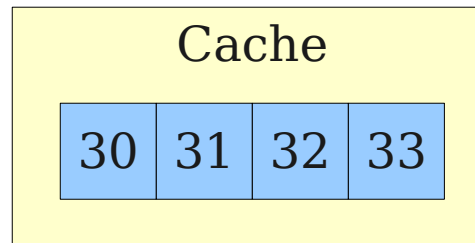
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Improving Locality

- Programmers frequently write code without understanding the locality implications.
 - Languages don't expose low-level memory details.
- Some compilers are capable of rewriting code to take advantage of locality.
- Cool optimizations:
 - Loop reordering.
 - Structure peeling.

Loop Reordering

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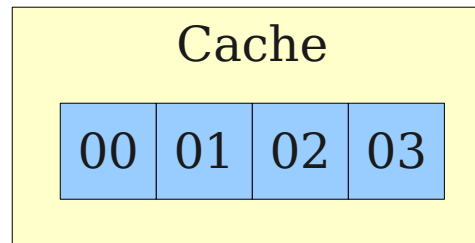
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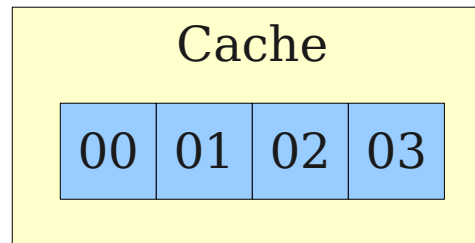
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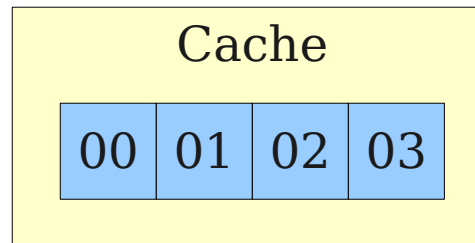
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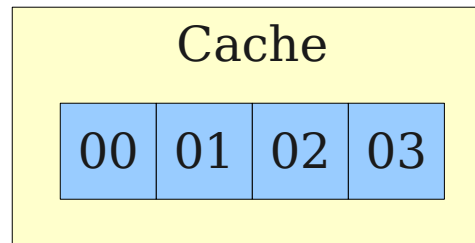
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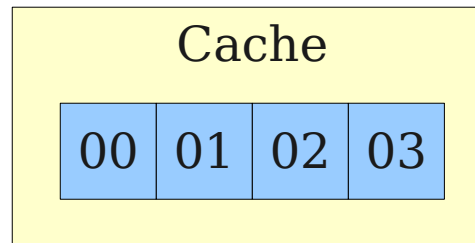
00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----



Loop Reordering

```
int[][] array;  
for (i = 0; i < 4; i = i + 1)  
    for (j = 0; j < 4; j = j + 1)  
        array[i][j] = 0;
```

00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----



Loop Reordering

```
int[][] array;  
for (i = 0; i < 4; i = i + 1)  
    for (j = 0; j < 4; j = j + 1)  
        array[i][j] = 0;
```

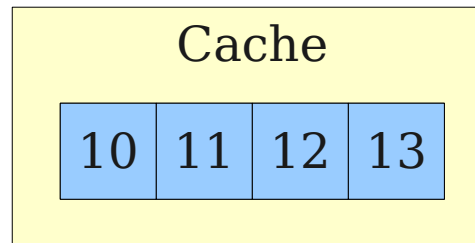
00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----

Cache

Loop Reordering

```
int[][] array;  
for (i = 0; i < 4; i = i + 1)  
    for (j = 0; j < 4; j = j + 1)  
        array[i][j] = 0;
```

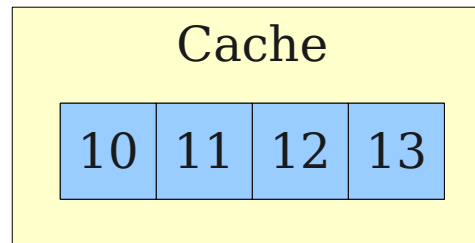
00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----



Loop Reordering

```
int[][] array;  
for (i = 0; i < 4; i = i + 1)  
    for (j = 0; j < 4; j = j + 1)  
        array[i][j] = 0;
```

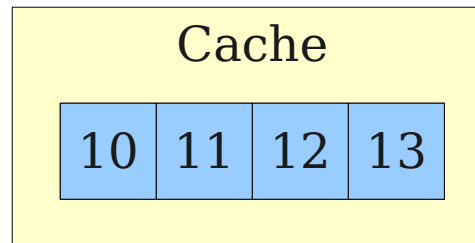
00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----



Loop Reordering

```
int[][] array;  
for (i = 0; i < 4; i = i + 1)  
    for (j = 0; j < 4; j = j + 1)  
        array[i][j] = 0;
```

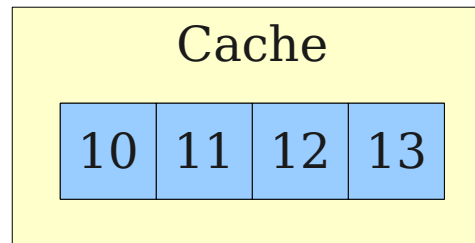
00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----



Loop Reordering

```
int[][] array;  
for (i = 0; i < 4; i = i + 1)  
    for (j = 0; j < 4; j = j + 1)  
        array[i][j] = 0;
```

00	01	02	03	10	11	12	13	20	21	22	23	30	31	32	33
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----



Structure Peeling

Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}
```

Structure Peeling

```
class Point2D {
    int x;
    int y;
}

void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```

Structure Peeling

```
class Point2D {
    int x;
    int y;
}

void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```

pts[0].x

pts[0].y

pts[1].x

pts[1].y

pts[2].x

pts[2].y

pts[3].x

pts[3].y

pts[4].x

pts[4].y

pts[5].x

pts[5].y

...

Structure Peeling

```
class Point2D {
    int x;
    int y;
}

void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```

pts[0].x

pts[0].y

pts[1].x

pts[1].y

pts[2].x

pts[2].y

pts[3].x

pts[3].y

pts[4].x

pts[4].y

pts[5].x

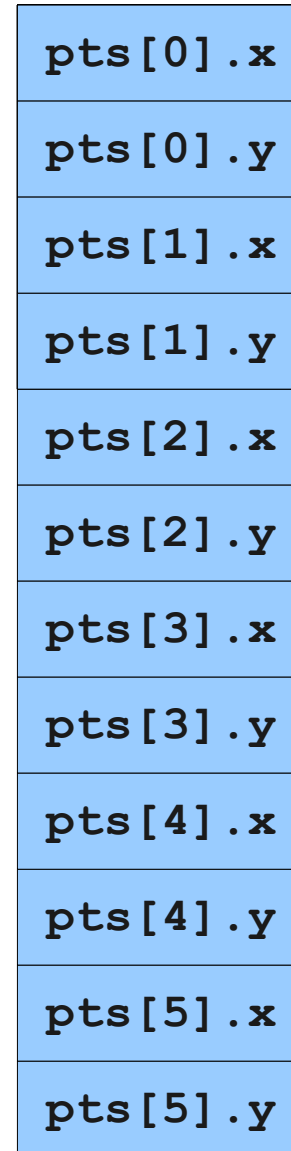
pts[5].y

...

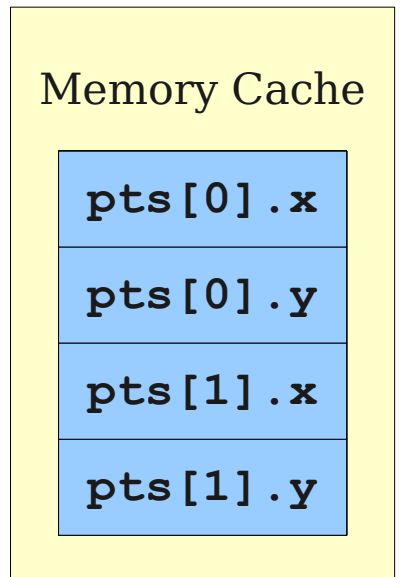
Memory Cache

Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```



...



Structure Peeling

```
class Point2D {
    int x;
    int y;
}

void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```

pts[0].x

pts[0].y

pts[1].x

pts[1].y

pts[2].x

pts[2].y

pts[3].x

pts[3].y

pts[4].x

pts[4].y

pts[5].x

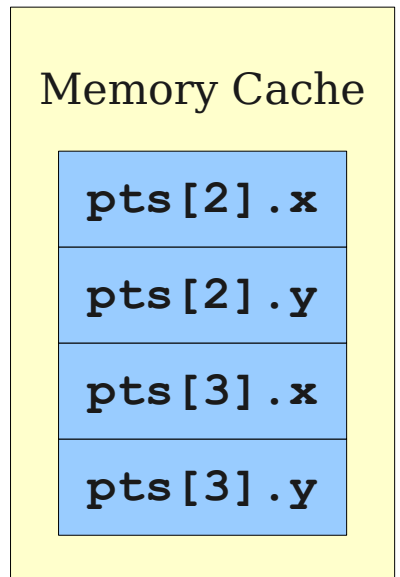
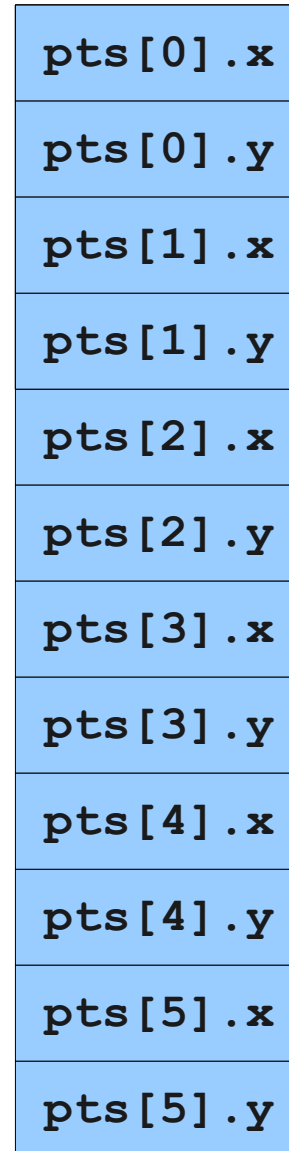
pts[5].y

...

Memory Cache

Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```



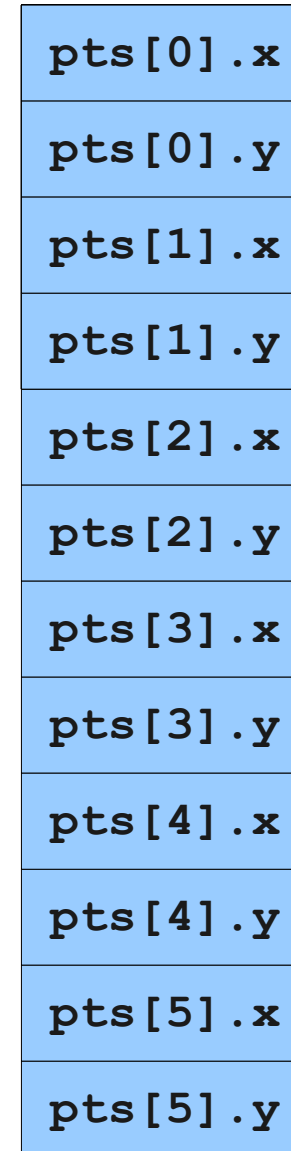
Structure Peeling

```
class Point2D {
    int x;
    int y;
}

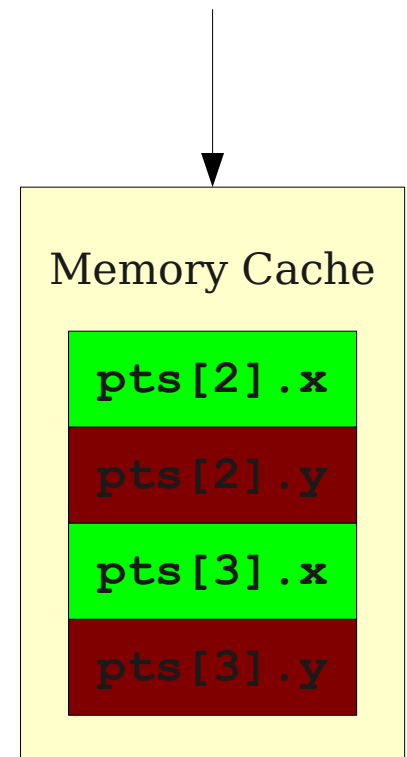
void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```

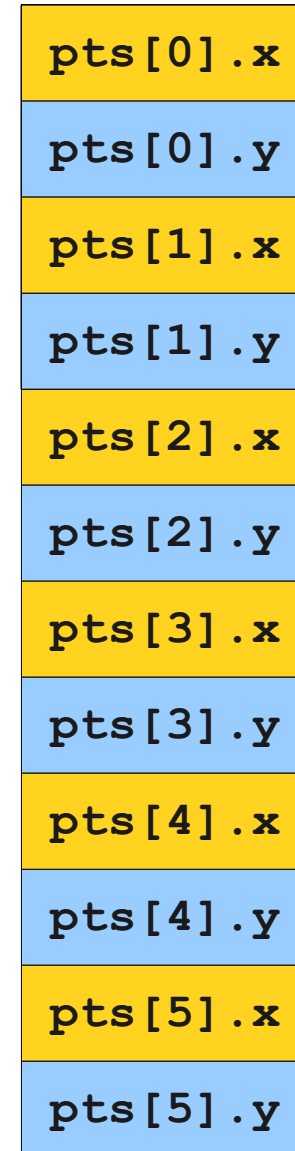


Only half
the cache
is useful!



Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```

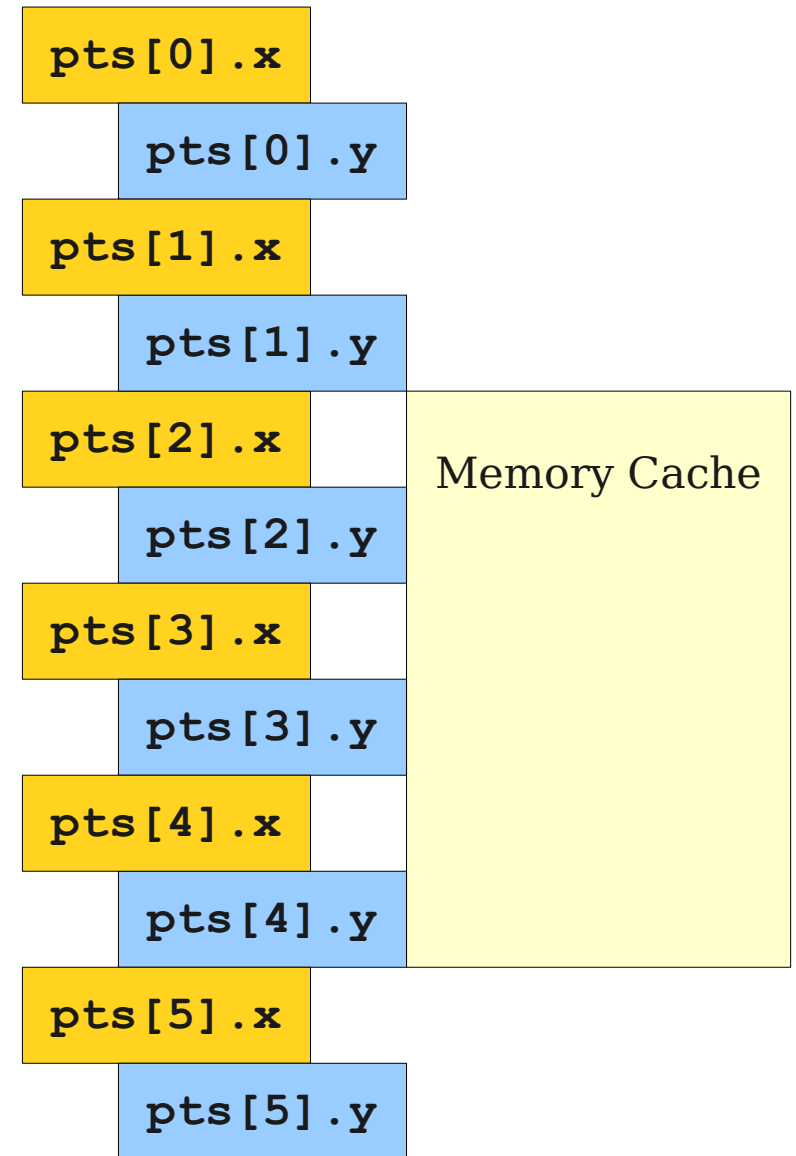


Memory Cache

...

Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```



...

Structure Peeling

```
class Point2D {
    int x;
    int y;
}

void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```

pts[0].x

pts[1].x

pts[2].x

pts[3].x

pts[4].x

...

pts[0].y

pts[1].y

pts[2].y

pts[3].y

pts[4].y

...

Memory Cache

Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```

pts[0].x

pts[1].x

pts[2].x

pts[3].x

pts[4].x

...

pts[0].y

pts[1].y

pts[2].y

pts[3].y

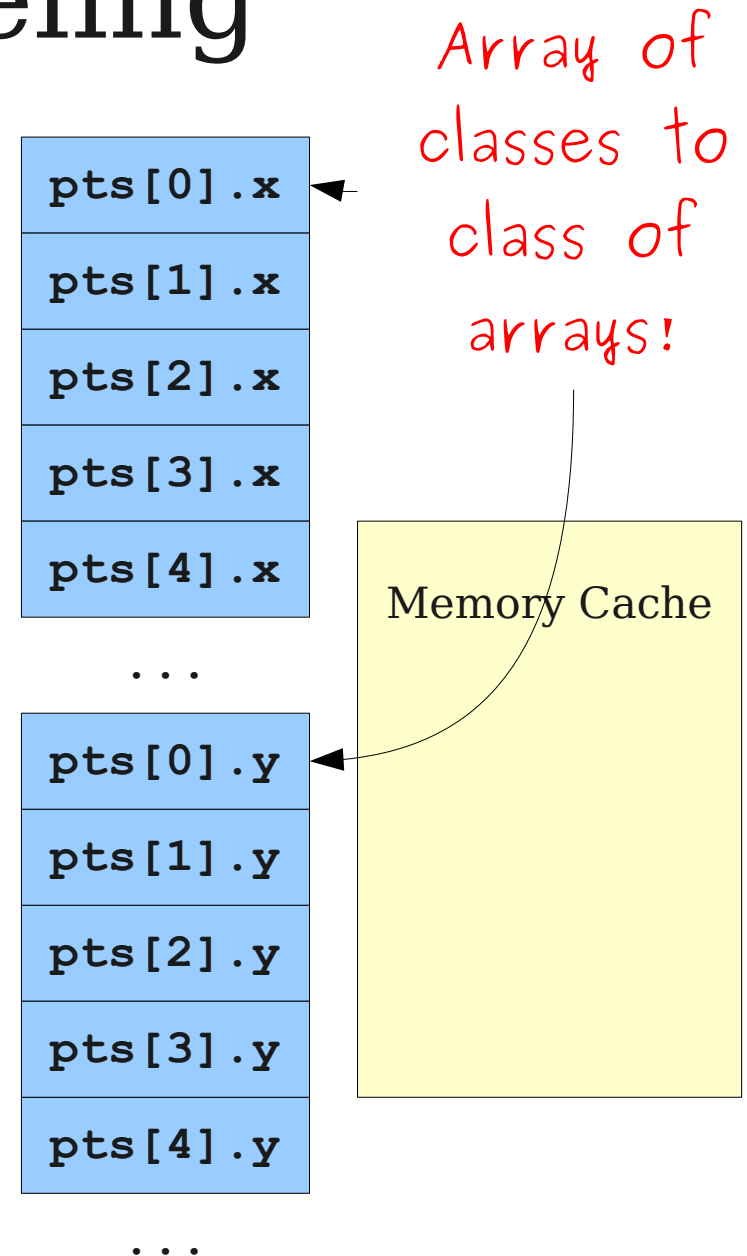
pts[4].y

...

Memory Cache

Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```



Structure Peeling

```
class Point2D {  
    int x;  
    int y;  
}  
  
void MyFunction() {  
    Point2D[] pts = new Point2D[1024];  
  
    /* ... initialize the points ... */  
  
    int maxX = 0, maxY = 0;  
    for (int i = 0; i < 512; ++i)  
        maxX = max(pts[i].x, maxX);  
    for (int i = 512; i < 1024; ++i)  
        maxY = max(pts[i].y, maxY);  
}
```

pts[0].x

pts[1].x

pts[2].x

pts[3].x

pts[4].x

...

pts[0].y

pts[1].y

pts[2].y

pts[3].y

pts[4].y

...

Memory Cache

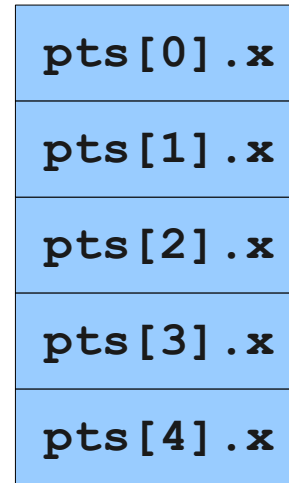
Structure Peeling

```
class Point2D {
    int x;
    int y;
}

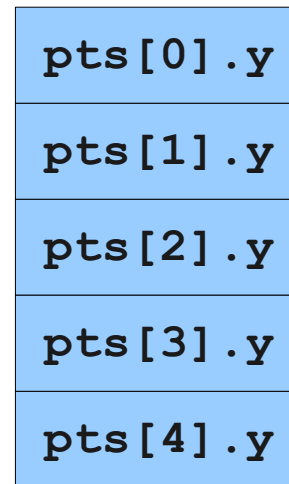
void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

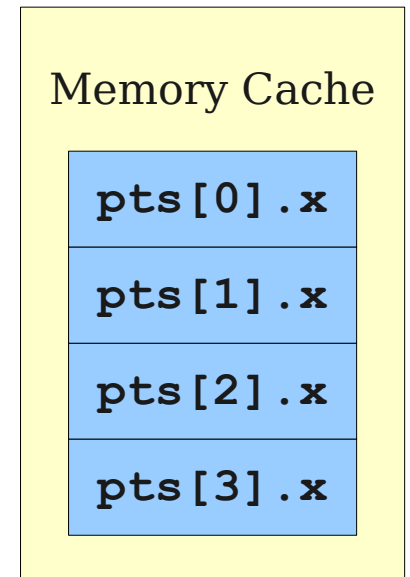
    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```



...



...



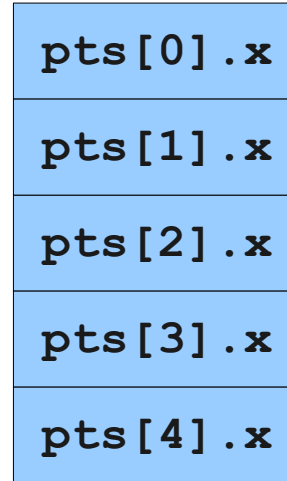
Structure Peeling

```
class Point2D {
    int x;
    int y;
}

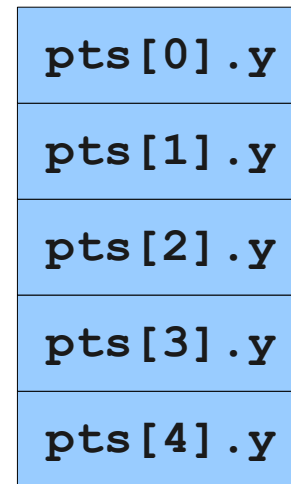
void MyFunction() {
    Point2D[] pts = new Point2D[1024];

    /* ... initialize the points ... */

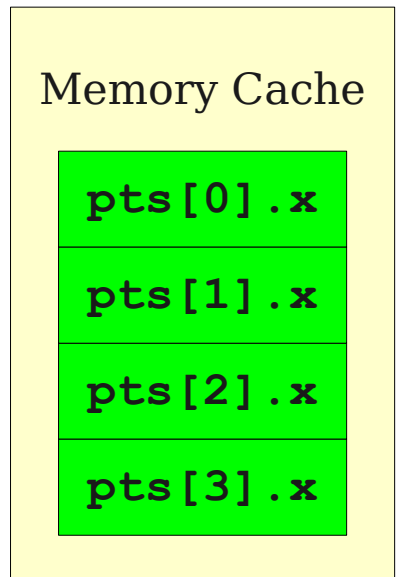
    int maxX = 0, maxY = 0;
    for (int i = 0; i < 512; ++i)
        maxX = max(pts[i].x, maxX);
    for (int i = 512; i < 1024; ++i)
        maxY = max(pts[i].y, maxY);
}
```



...



...



Optimizations for Parallelism

Everything is Parallel Now

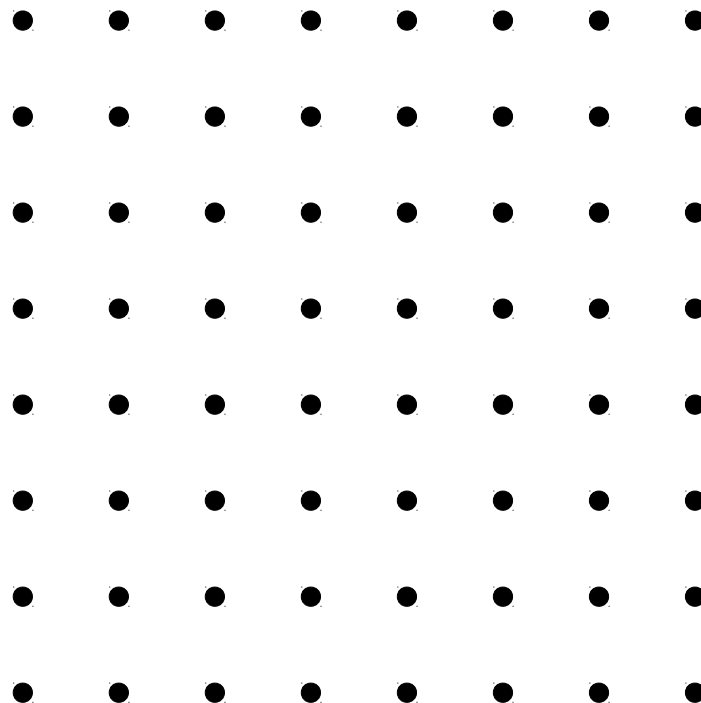
- Virtually all new computers have multiple processors.
 - Even some phones have multiple cores!
- High-end machines now usually have at least eight cores.
- How do we optimize code to work well in parallel?

Loop Parallelization

- Many numeric computations work by iterating over large arrays of elements.
 - Especially true in FORTRAN code.
- Optimize loops over arrays by identifying inherent parallelism.
- Three-step process:
 - Identify which array values depend on one another.
 - Split each group of dependent values into its own task.
 - Map each task onto one processor.
- Beautiful (but tricky!) framework for doing this automatically; I'm not even going to try to go into mathematical details.

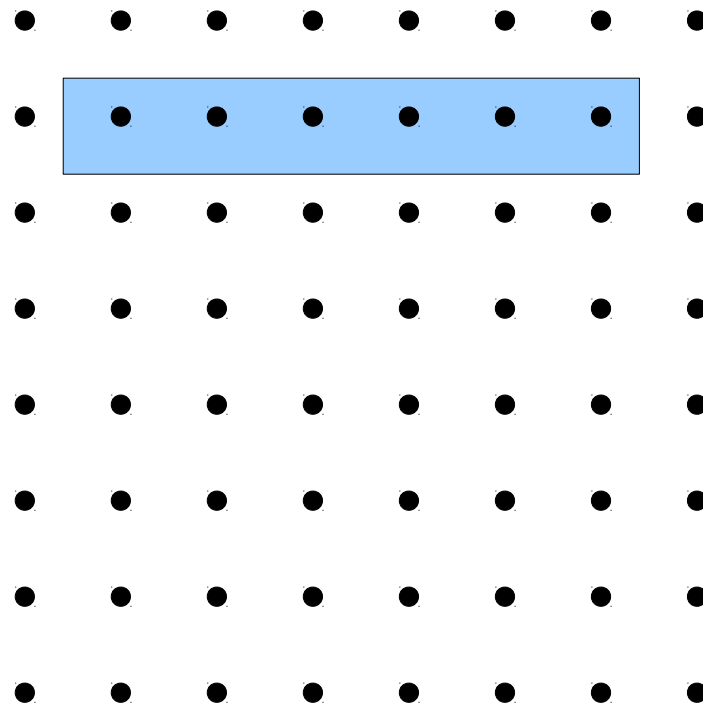
Iteration Spaces

- The **iteration space** of a set of loops is the set of valid indices taken by the loop counters.



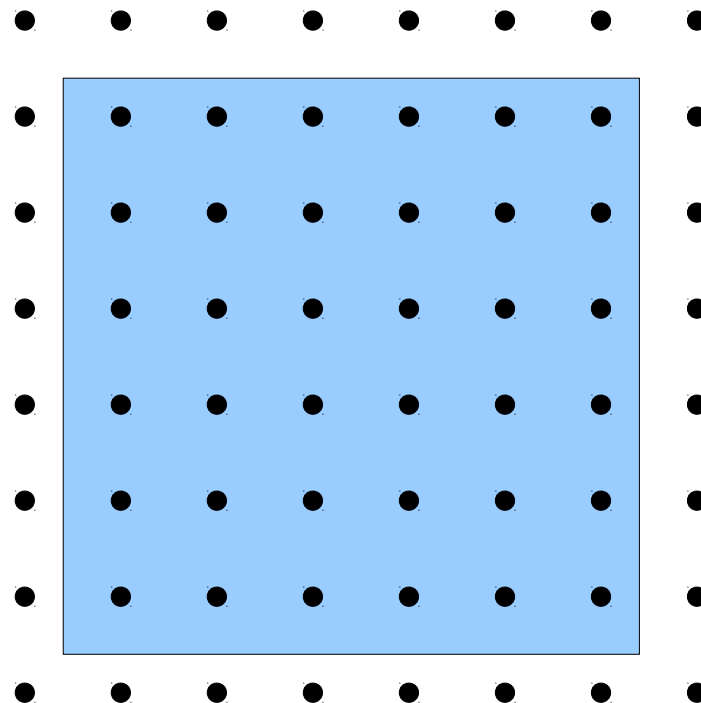
Iteration Spaces

- The **iteration space** of a set of loops is the set of valid indices taken by the loop counters.



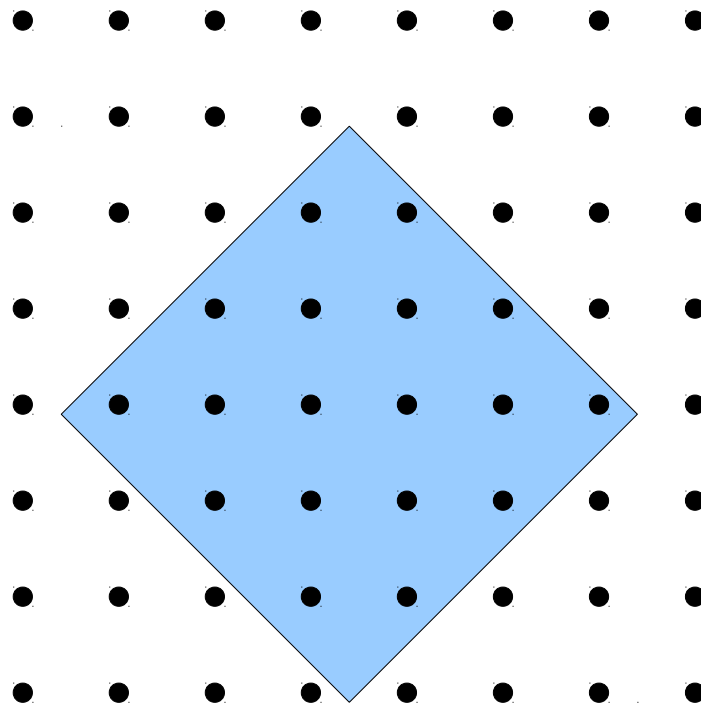
Iteration Spaces

- The **iteration space** of a set of loops is the set of valid indices taken by the loop counters.



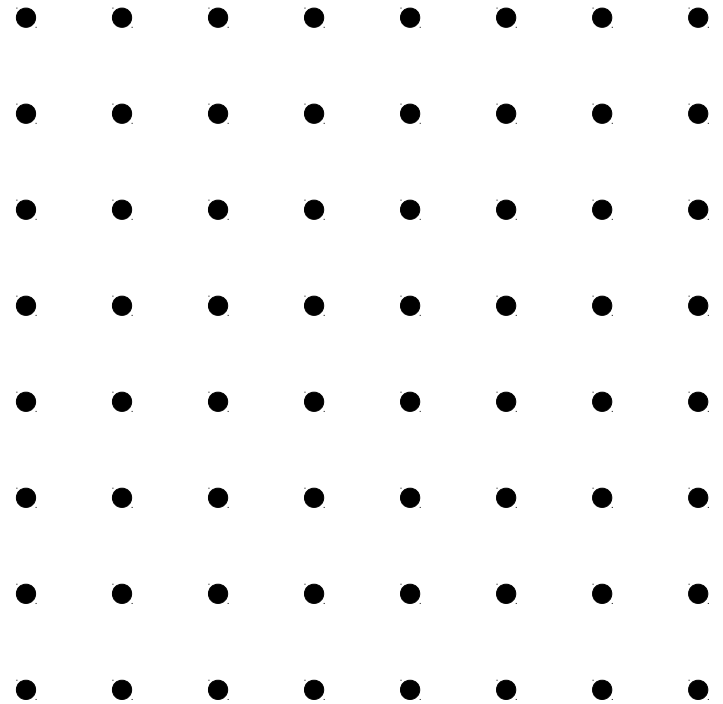
Iteration Spaces

- The **iteration space** of a set of loops is the set of valid indices taken by the loop counters.



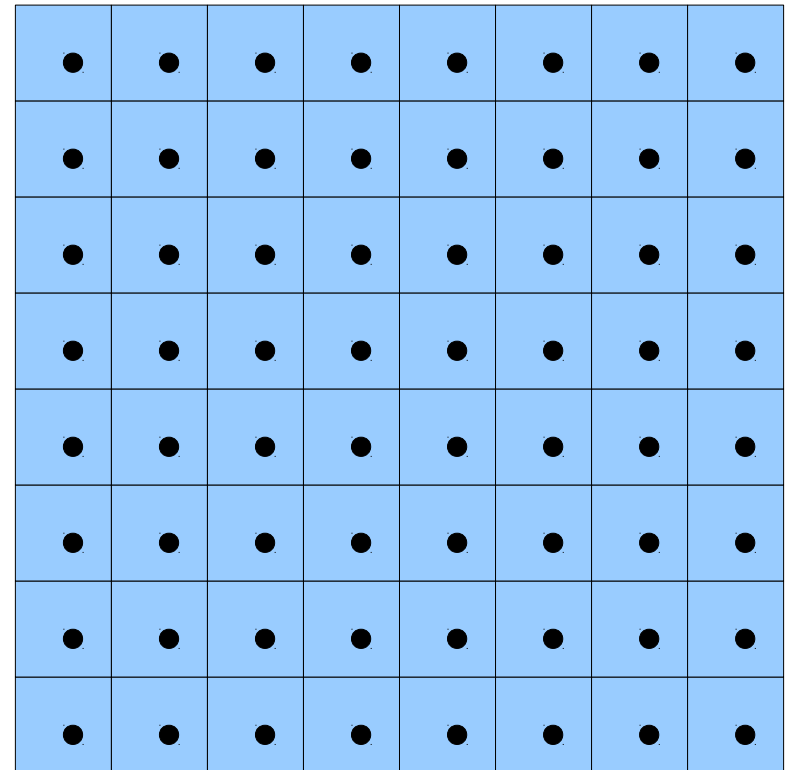
Identifying Dependent Accesses

```
for (int i = 0; i < 8; ++i)
  for (int j = 0; j < 8; ++j)
    arr[i][j] = 0;
```



Identifying Dependent Accesses

```
for (int i = 0; i < 8; ++i)
  for (int j = 0; j < 8; ++j)
    arr[i][j] = 0;
```



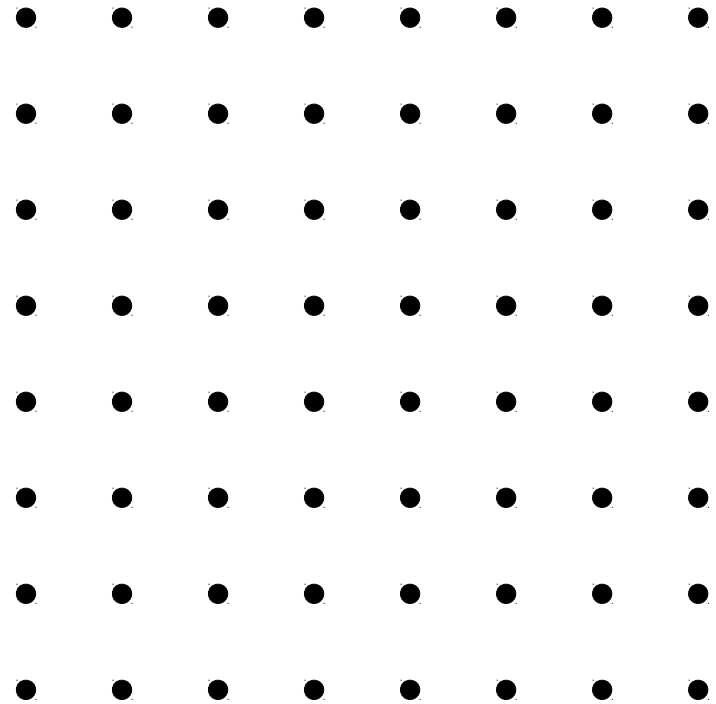
Identifying Dependent Accesses

Identifying Dependent Accesses

```
for (int i = 0; i < 8; ++i)
    for (int j = 1; j < 8; ++j)
        arr[i][j] = arr[i][j-1];
```

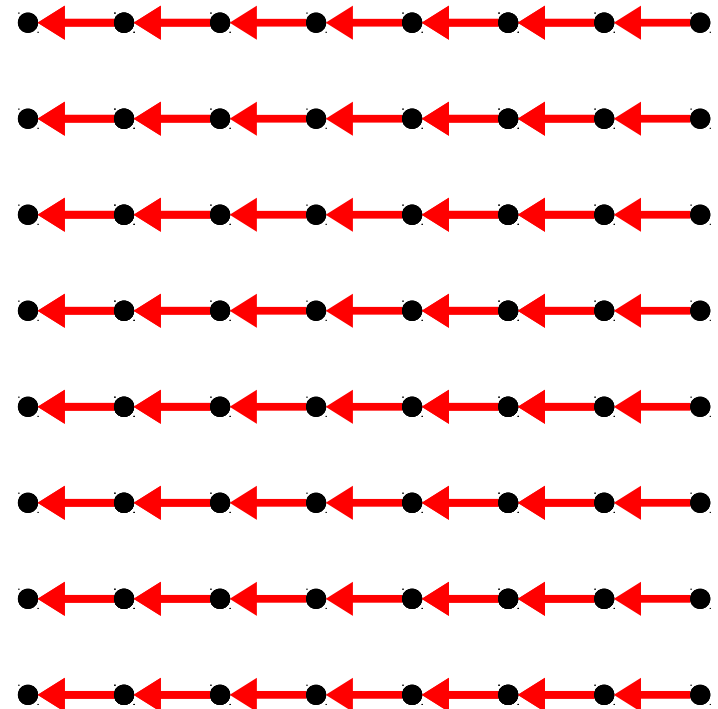
Identifying Dependent Accesses

```
for (int i = 0; i < 8; ++i)
  for (int j = 1; j < 8; ++j)
    arr[i][j] = arr[i][j-1];
```



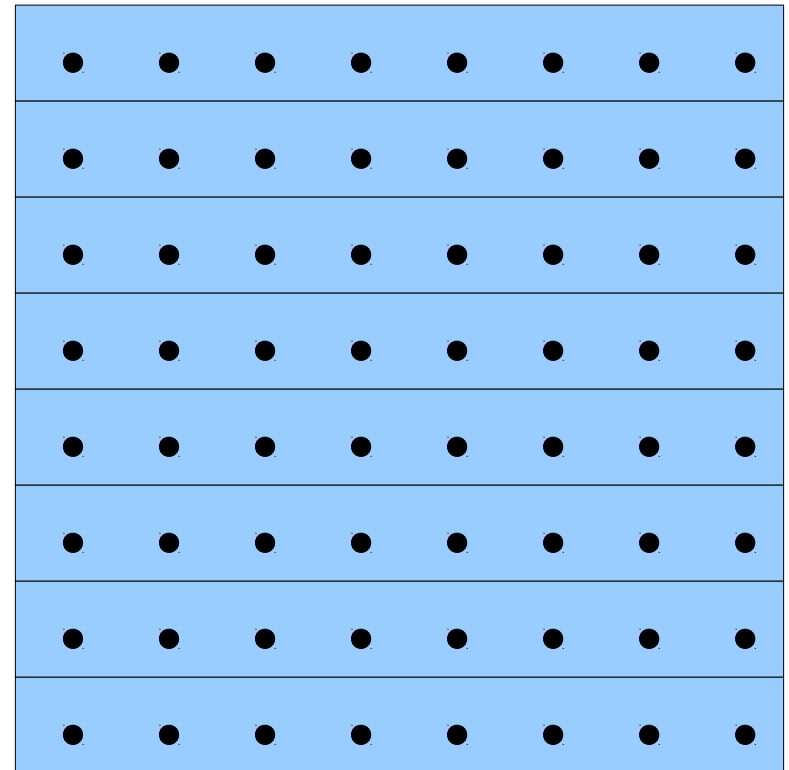
Identifying Dependent Accesses

```
for (int i = 0; i < 8; ++i)
  for (int j = 1; j < 8; ++j)
    arr[i][j] = arr[i][j-1];
```



Identifying Dependent Accesses

```
for (int i = 0; i < 8; ++i)
  for (int j = 1; j < 8; ++j)
    arr[i][j] = arr[i][j-1];
```



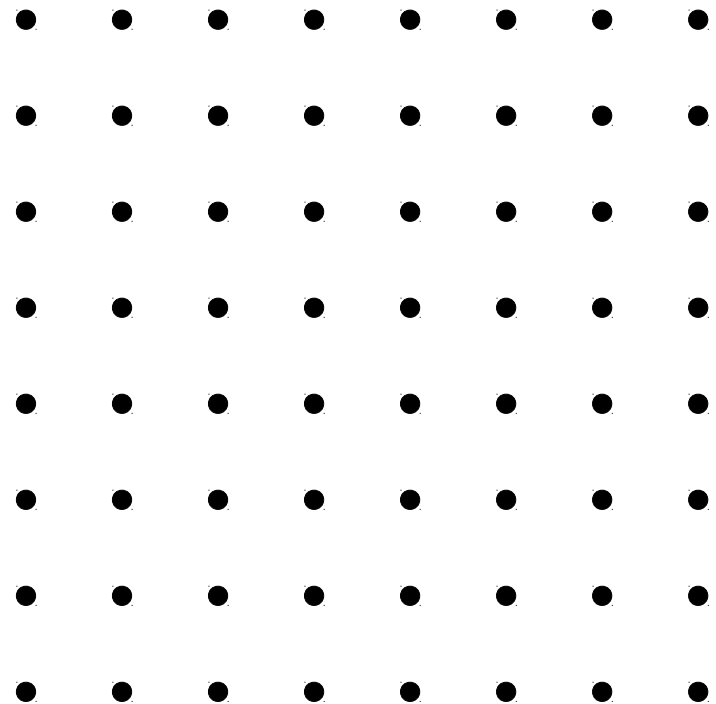
Identifying Dependent Accesses

Identifying Dependent Accesses

```
for (int i = 1; i < 8; ++i)
    for (int j = 1; j < 8; ++j)
        arr[i][i] = arr[i][j-1] +
                     arr[i-1][j] +
                     arr[i-1][j-1];
```

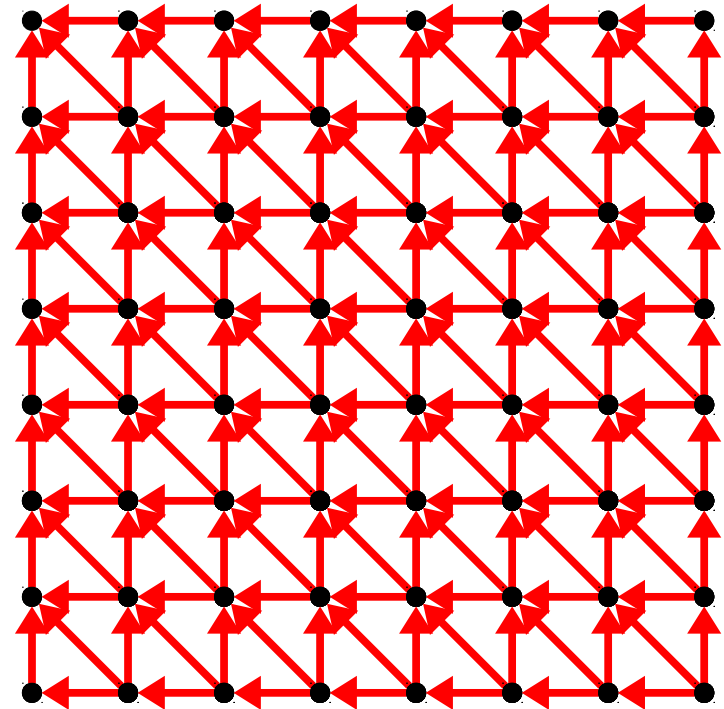
Identifying Dependent Accesses

```
for (int i = 1; i < 8; ++i)
  for (int j = 1; j < 8; ++j)
    arr[i][i] = arr[i][j-1] +
                 arr[i-1][j] +
                 arr[i-1][j-1];
```



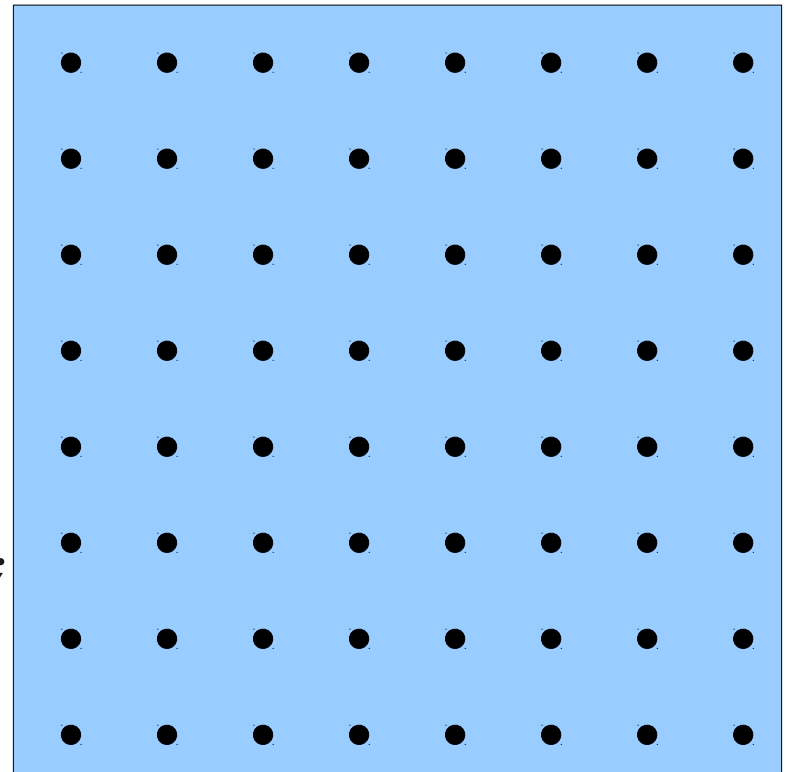
Identifying Dependent Accesses

```
for (int i = 1; i < 8; ++i)
  for (int j = 1; j < 8; ++j)
    arr[i][i] = arr[i][j-1] +
                 arr[i-1][j] +
                 arr[i-1][j-1];
```



Identifying Dependent Accesses

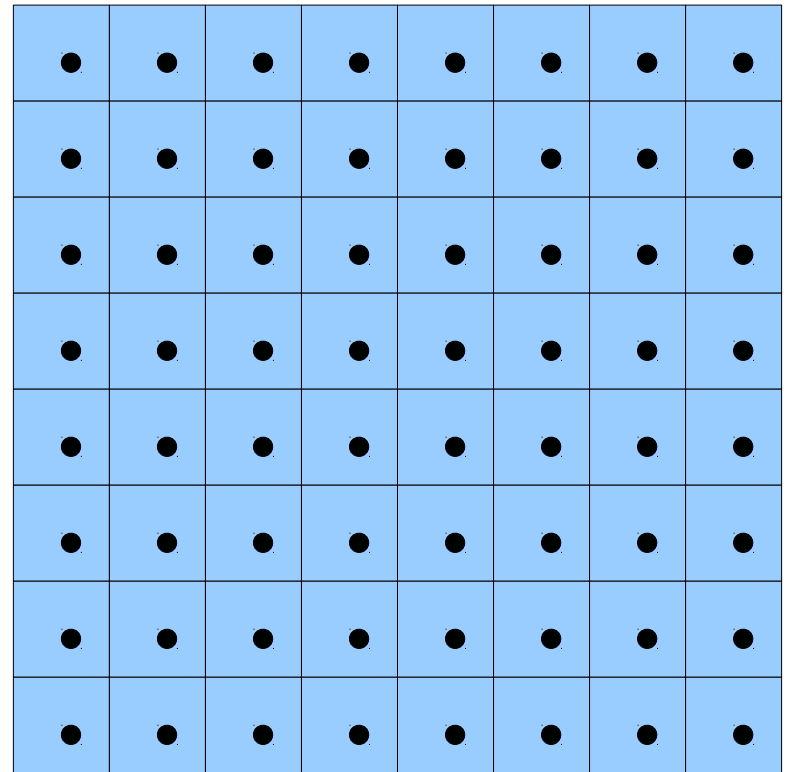
```
for (int i = 1; i < 8; ++i)
  for (int j = 1; j < 8; ++j)
    arr[i][i] = arr[i][j-1] +
                 arr[i-1][j] +
                 arr[i-1][j-1];
```



Assigning Groups to Processors

Assigning Groups to Processors

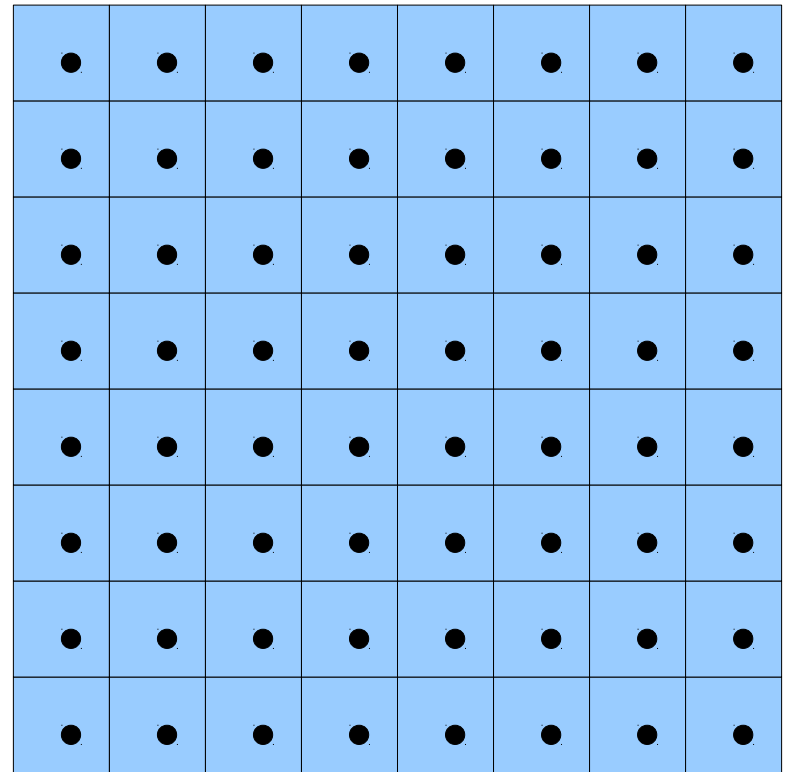
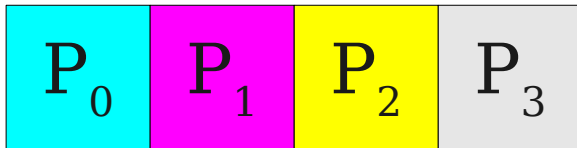
```
for (int i = 0; i < 8; ++i)
  for (int j = 0; j < 8; ++j)
    arr[i][j] = 0;
```



Assigning Groups to Processors

```
for (int i = 0; i < 8; ++i)
  for (int j = 0; j < 8; ++j)
    arr[i][j] = 0;
```

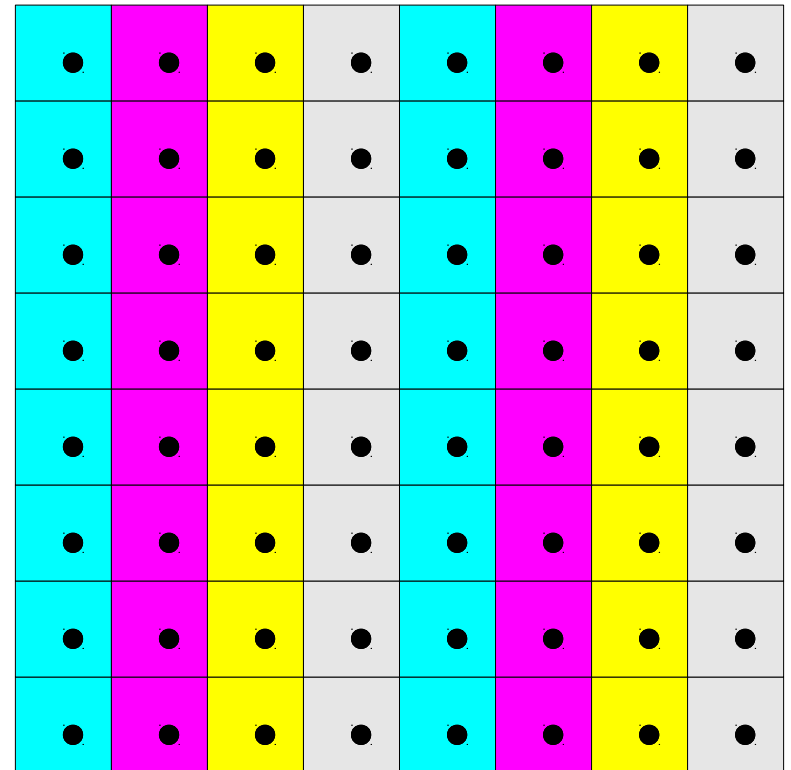
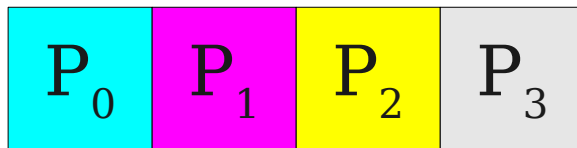
Processors



Assigning Groups to Processors

```
for (int i = 0; i < 8; ++i)
    for (int j = 0; j < 8; ++j)
        arr[i][j] = 0;
```

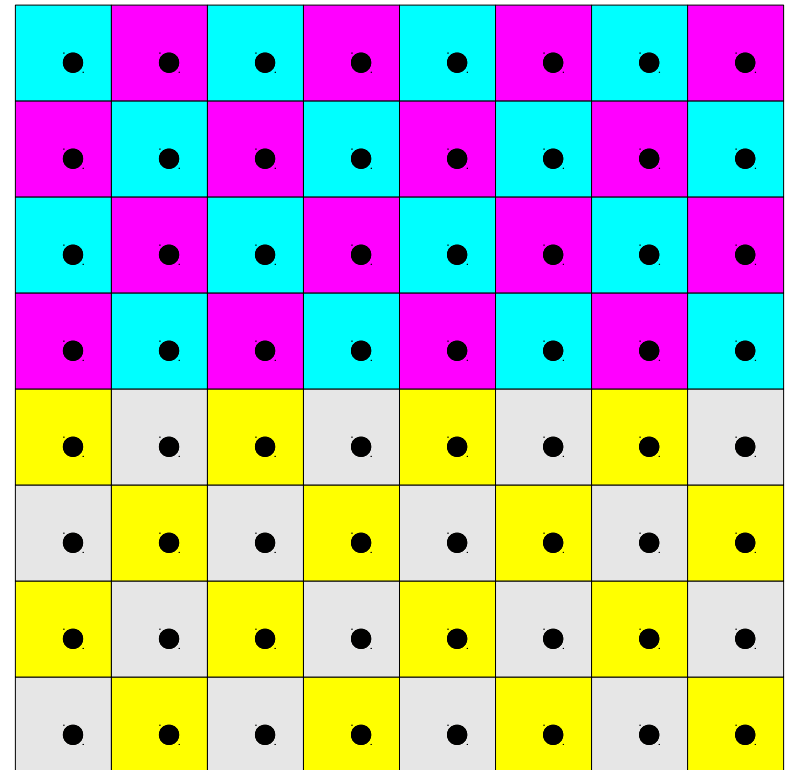
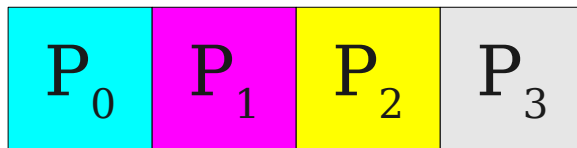
Processors



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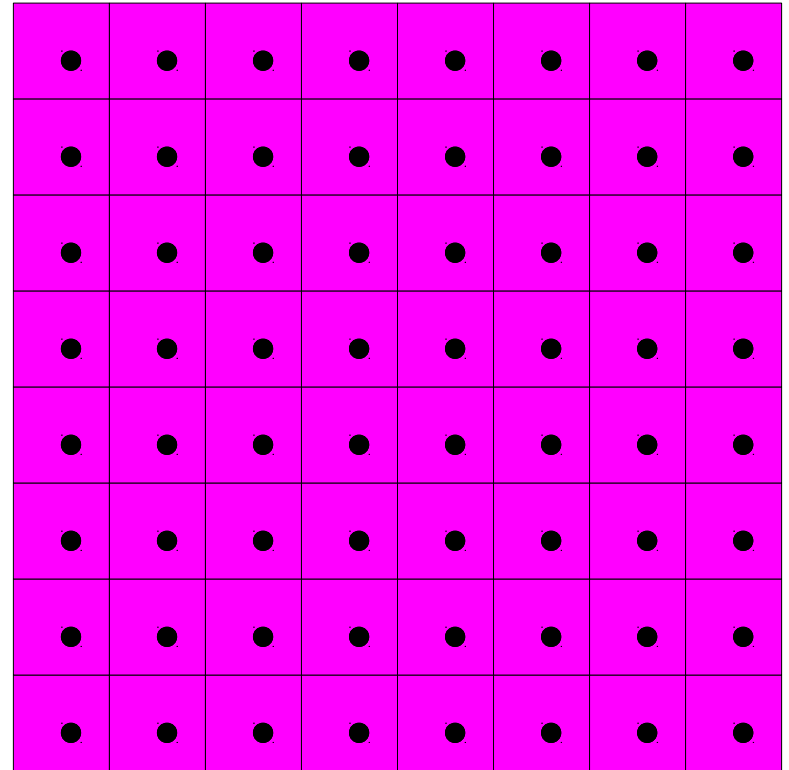
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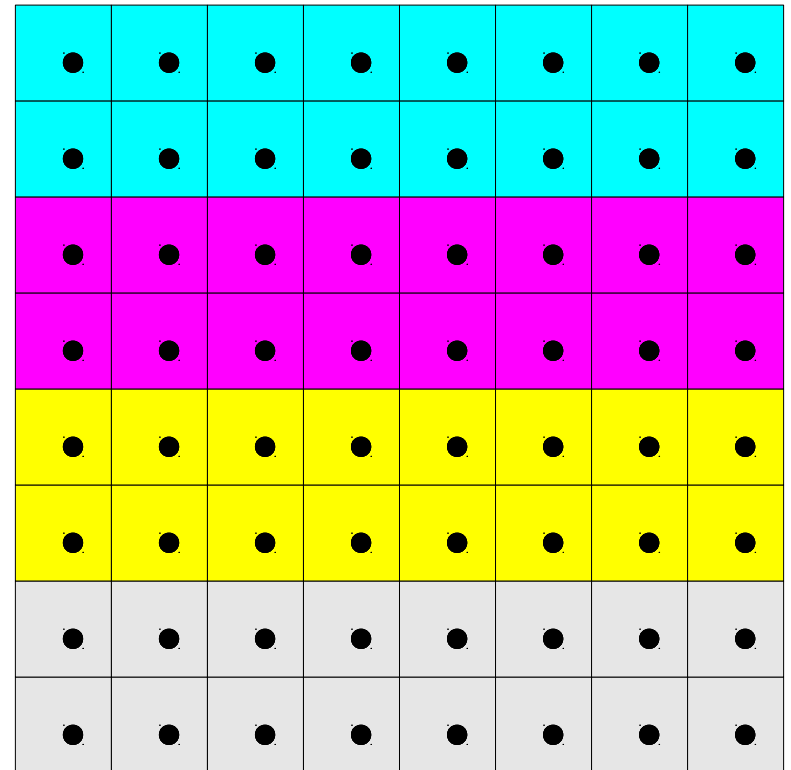
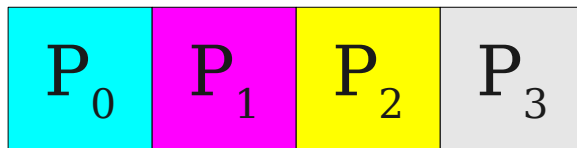
Processors



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Processors



Assignment Considerations

- When assigning iterations to processors:
 - Pick an assignment that is good for locality.
 - Pick an assignment that maximizes the degree of parallelism.
- In many cases, can be determined automatically!
 - See Ch. 11 of the Dragon Book.

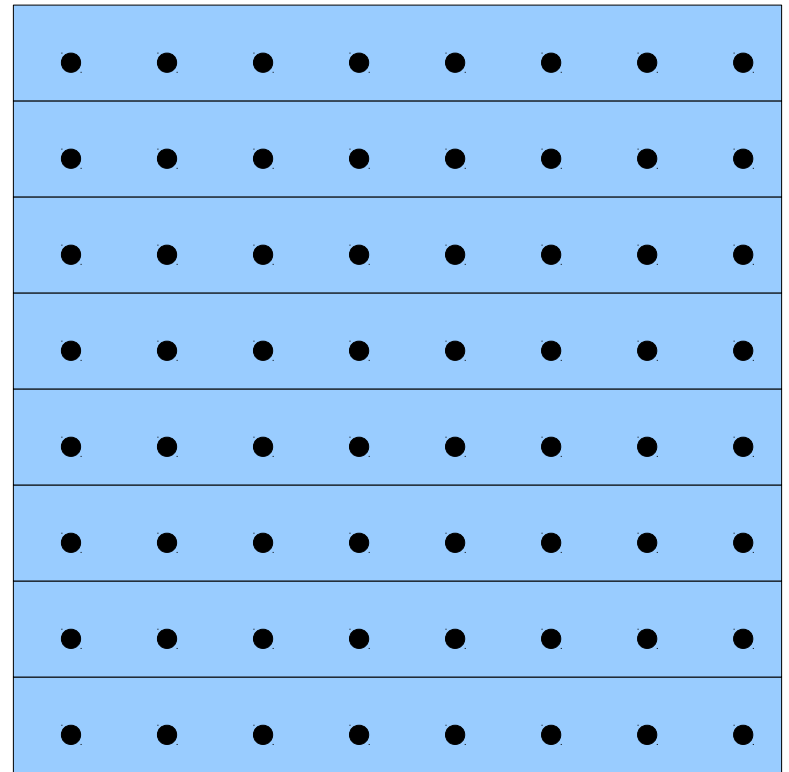
Assigning Groups to Processors

Assigning Groups to Processors

```
for (int i = 0; i < 8; ++i)
    for (int j = 1; j < 8; ++j)
        arr[i][j] = arr[i][j-1];
```


Assigning Groups to Processors

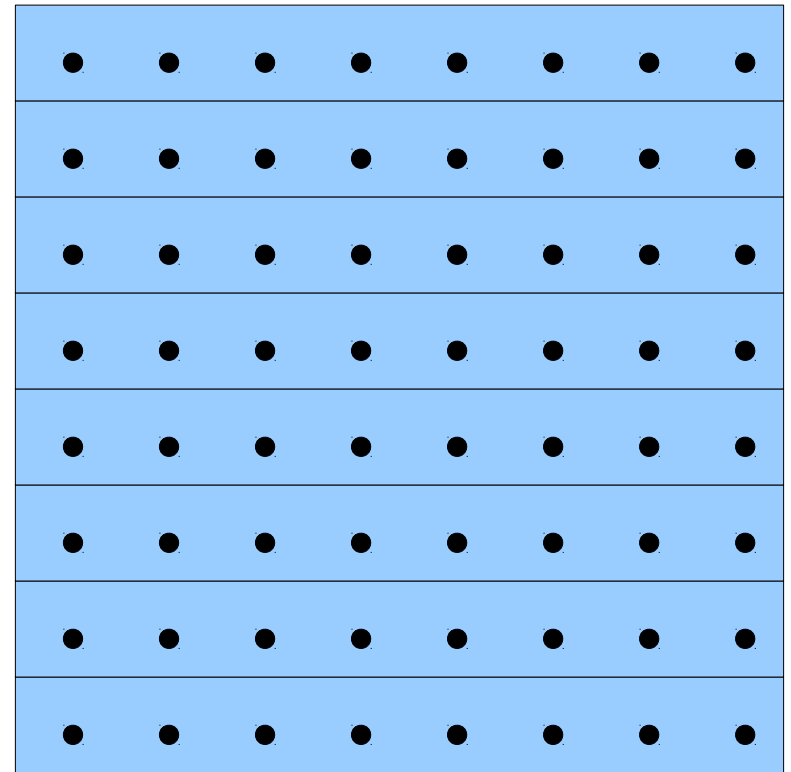
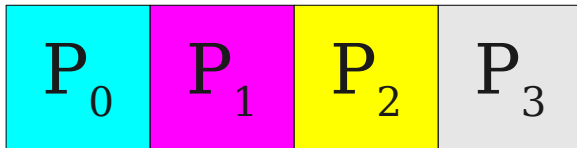
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Assigning Groups to Processors

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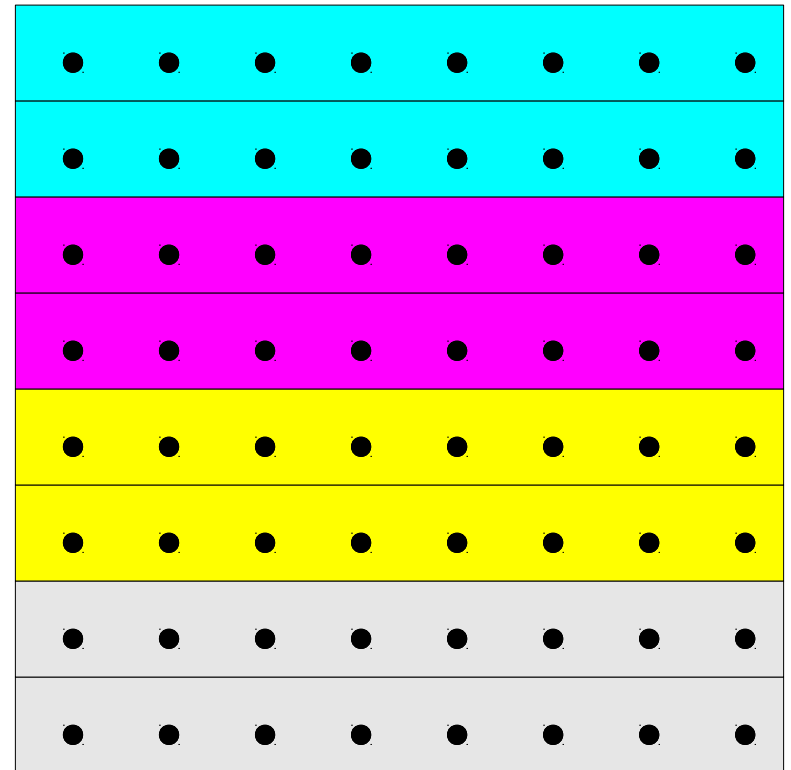
Processors



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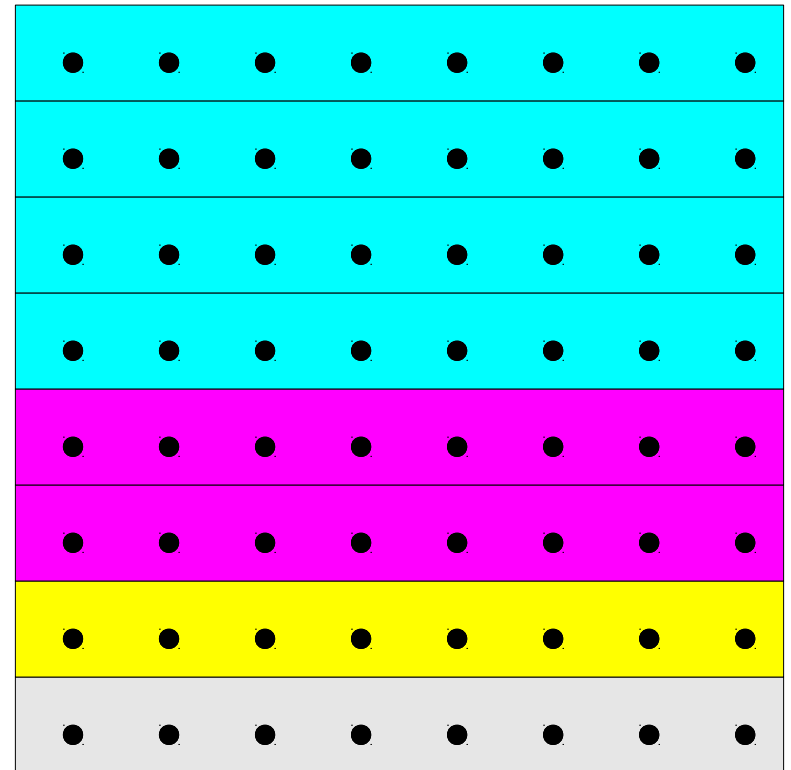
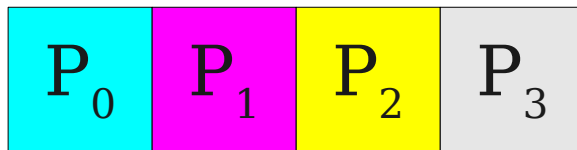
Processors



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Processors



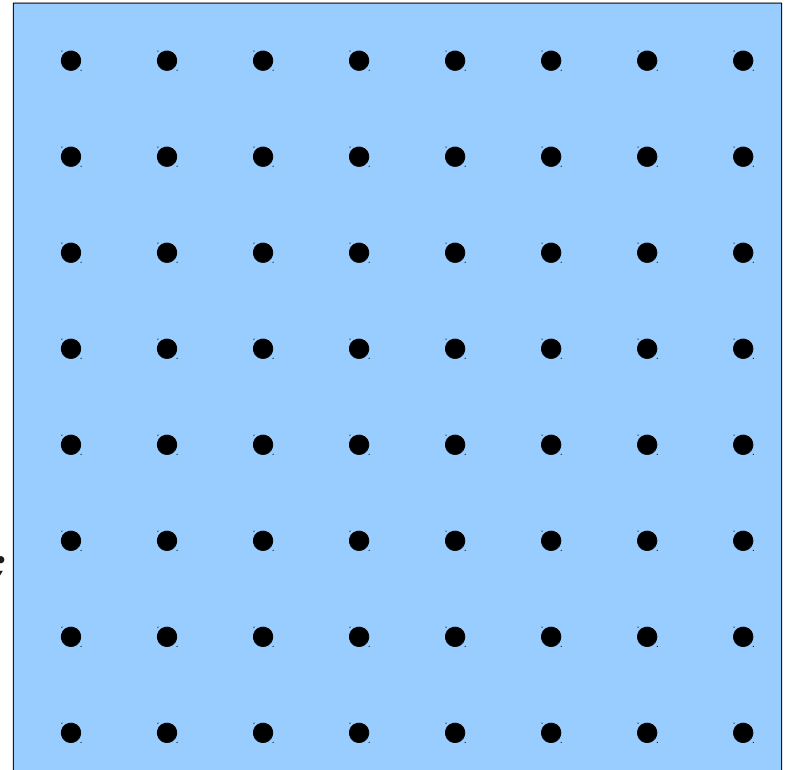
Assigning Groups to Processors

Assigning Groups to Processors

```
for (int i = 1; i < 8; ++i)
    for (int j = 1; j < 8; ++j)
        arr[i][i] = arr[i][j-1] +
                    arr[i-1][j] +
                    arr[i-1][j-1];
```

Assigning Groups to Processors

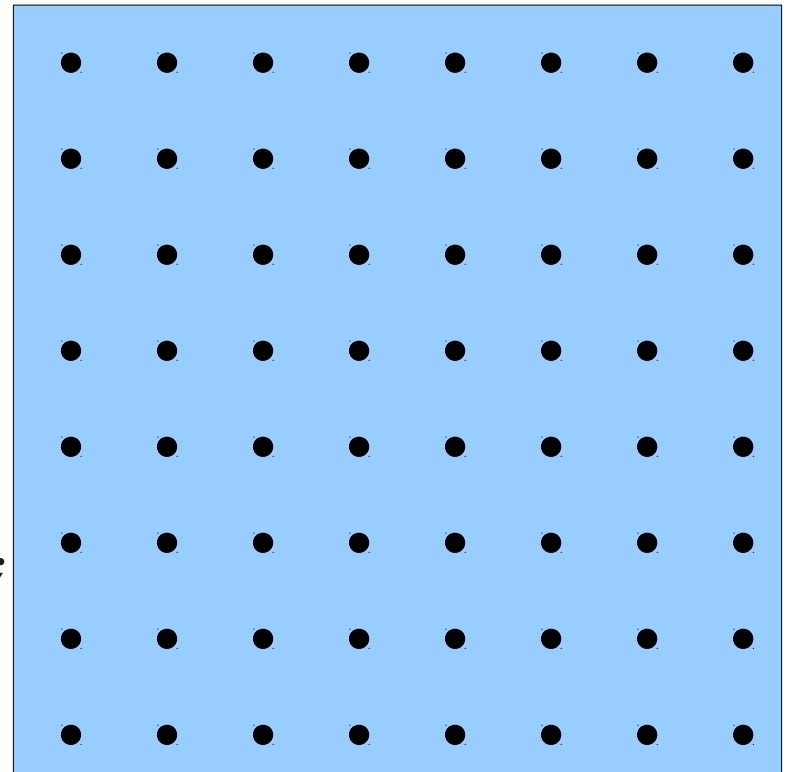
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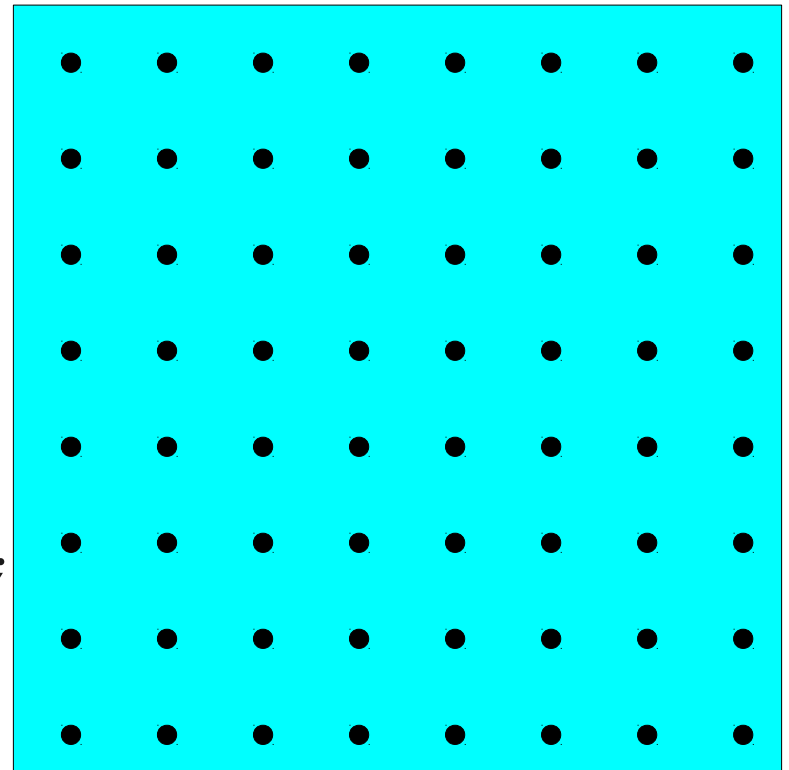
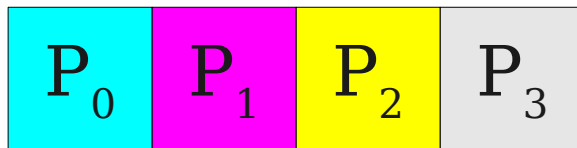
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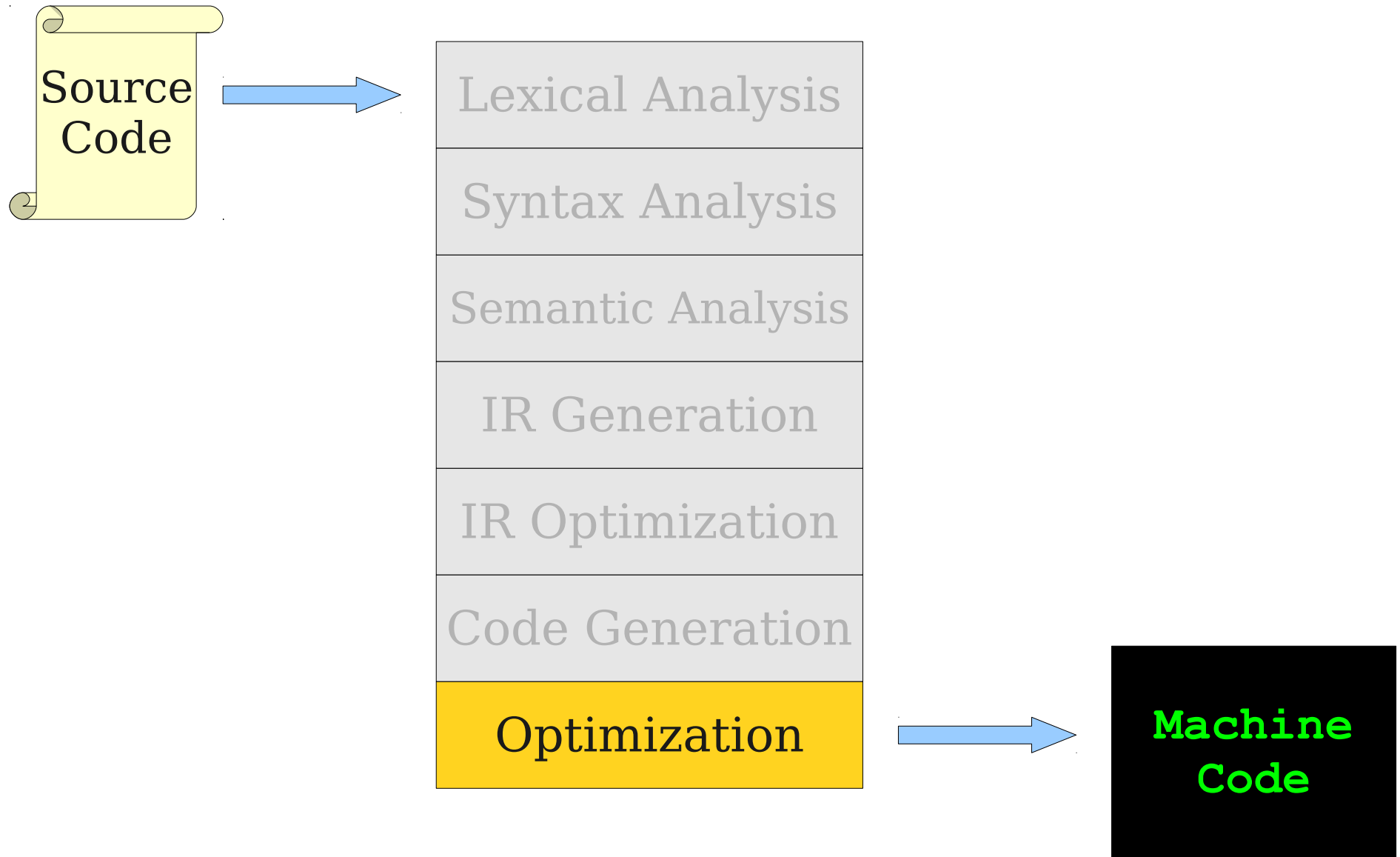
Processors



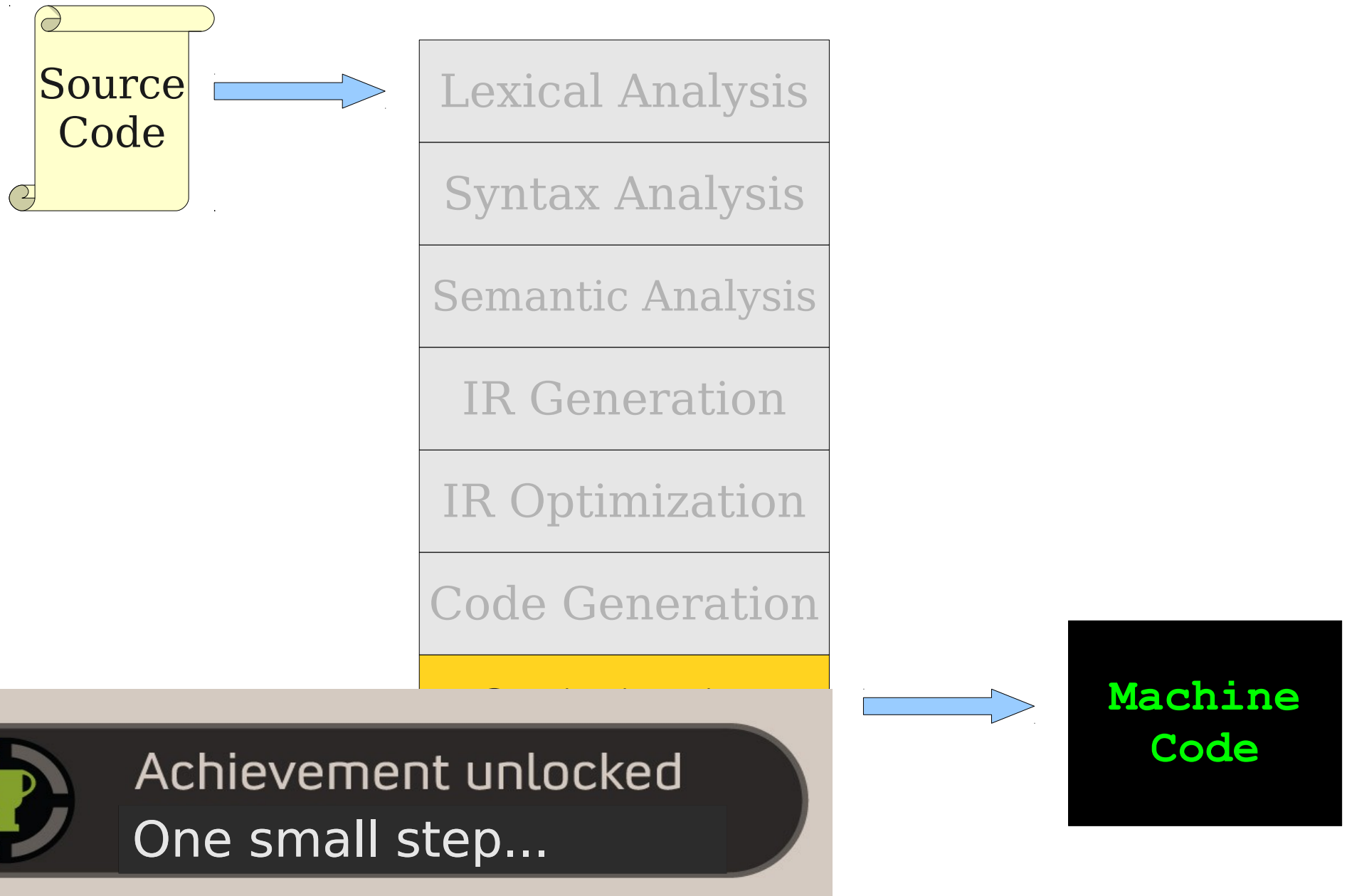
Summary

- **Instruction scheduling** optimizations try to take advantage of the processor pipeline.
- **Locality** optimizations try to take advantage of cache behavior.
- **Parallelism** optimizations try to take advantage of multicore machines.
- There are *many more* optimizations out there!

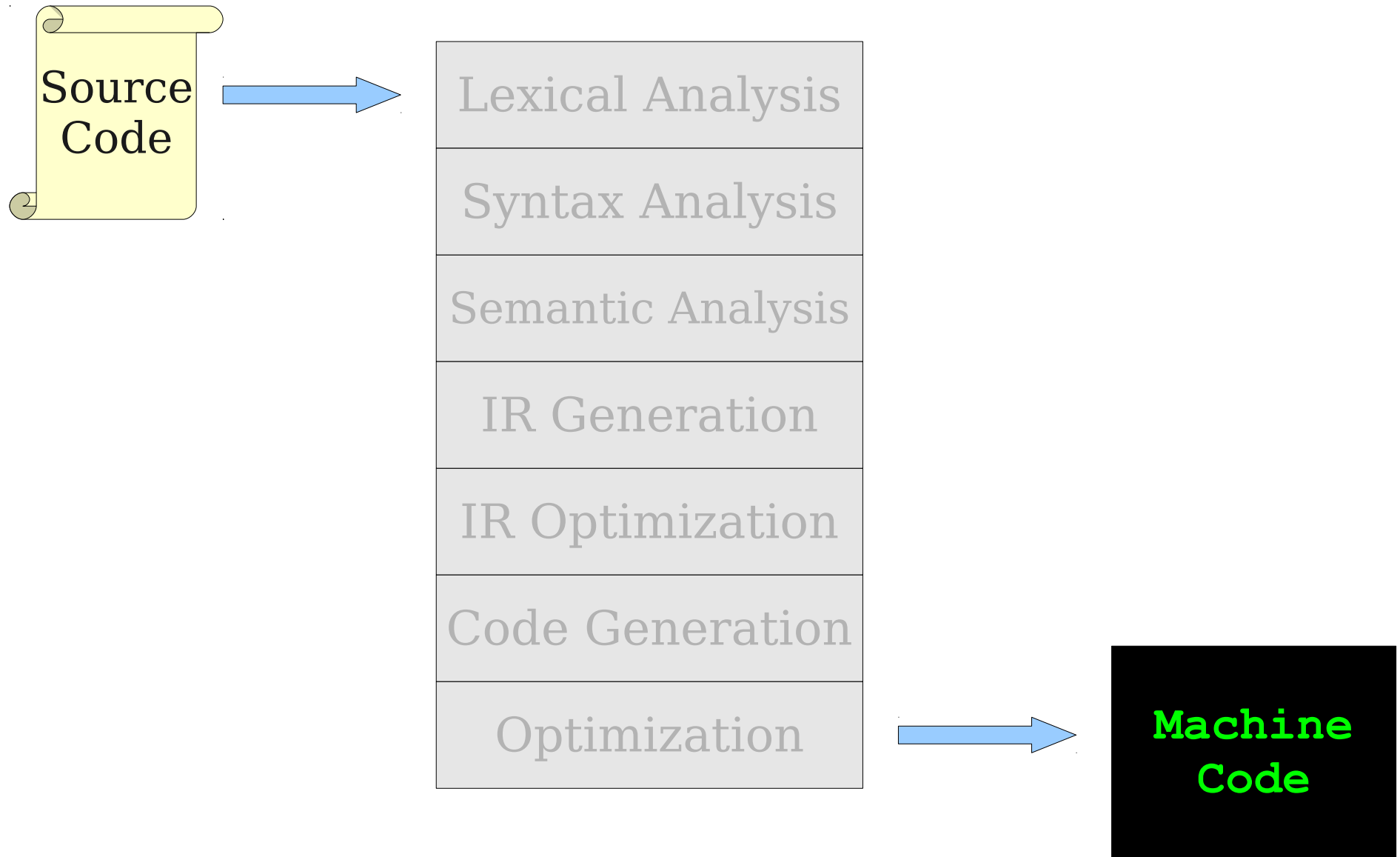
Where We Are



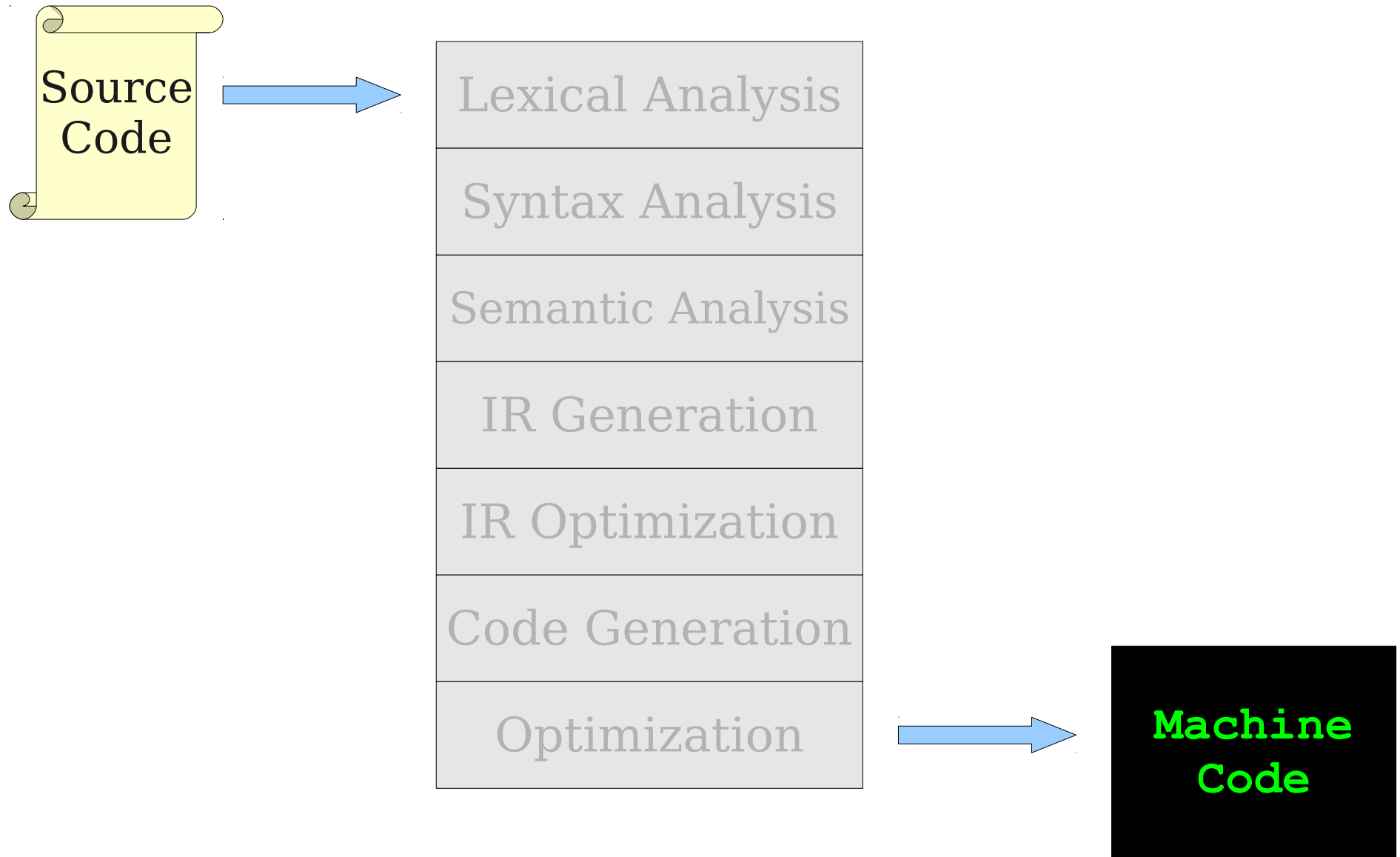
Where We Are



Where We Are



Where We've Been



Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization

- Regular Expressions
- Finite Automata
- Maximal-Munch
- Subset Construction
- **flex**

Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization

- Context-Free Grammars
- Parse Trees
- ASTs
- Leftmost DFS
- LL(1)
- Handles
- LR(0)
- SLR(1)
- LR(1)
- LALR(1)
- Earley
- Earley-on-DFA
- **bison**

Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization

- Scope-Checking
- Spaghetti Stacks
- Function Overloading
- Type Systems
- Well-Formedness
- Null and Error Types
- Covariance

Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization

- Runtime Environments
- Function Stacks
- Closures
- Coroutines
- Parameter Passing
- Object Layouts
- Vtables
- Inline Caching
- TAC

Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization

- Basic Blocks
- Control-Flow Graphs
- Common Subexpression Elimination
- Copy Propagation
- Dead Code Elimination
- Arithmetic Simplification
- Constant Folding
- Meet Semilattices
- Transfer Functions
- Global Constant Propagation
- Partial Redundancy Elimination

Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
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Code Generation
Optimization

- Memory Hierarchies
- Live Ranges
- Live Intervals
- Linear-Scan Register Allocation
- Register Interference Graphs
- Chaitin's Graph-Coloring Algorithm
- Reference Counting
- Mark-and-Sweep Collectors
- Baker's Algorithm
- Stop-and-Copy Collectors
- Generational Collectors

Where We've Been

Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization

- Instruction Scheduling
- Loop Reordering
- Structure Peeling
- Automatic Parallelization

Why Study Compilers? (Recap)

- Build a **large, ambitious software system**.
- See theory **come to life**.
- Learn how to **build programming languages**.
- Learn **how programming languages work**.
- Learn **tradeoffs in language design**.

Where to Go from Here

CS243: Program Analysis and Optimization

- In-depth treatment of optimization topics:
 - Dataflow framework.
 - Register allocation.
 - Garbage collection.
 - Instruction scheduling.
 - Locality optimizations.
 - Parallelization.
 - Interprocedural analysis.

CS242: Programming Languages

- Survey of programming languages, their innovations, and their implementations:
 - Functional programming.
 - Object-oriented languages through history.
 - Runtime environments and optimizations.
 - Language-level security.
 - Modern language features.

CS258: Intro to Programming Language Theory

- Mathematical exploration of programs and their properties:
 - Operational semantics.
 - Fixed-point operators and recursion.
 - Axiomatic semantics.
 - Formal algebras
 - Denotational semantics.

CS343: Advanced Topics in Compilers

- Research-level topics in compilers and interpreters:
 - Building fast JITs.
 - Binary translation.
 - Dynamic and static analysis.
 - Sandboxing.
 - Superoptimizers.

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htiek@cs.stanford.edu

Final Thoughts