Freeze After Writing:
Quasi-Deterministic Parallel Programming with LVars

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Aaron Turon
Neelakantan R. Krishnaswami
Ryan R. Newton

POPL '14, January 23, 2014

Freeze After Writing

- LVars
- Quasi-Deterministic

Parallel Programming

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data Item = Book | Shoes | ...
  deriving (Show, Ord, Eq)
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p :: IO (Map Item Int)
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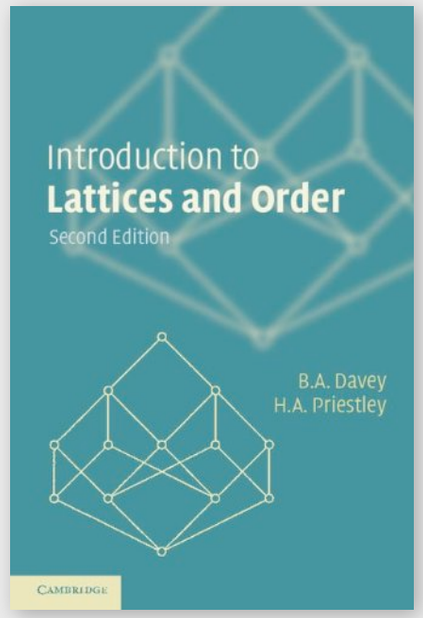

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       res <- async $ readIORef cart
       wait res
```

Terminal — bash — 90×27

bash

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landin:lvar-examples lkuper$ make map-ioref-data-race
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Linking map-ioref-data-race ...
while true; do ./map-ioref-data-race +RTS -N2; done
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       wait res                readIORef cart
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main = do v <- p
          putStr $ show $ toList v
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Deterministic,
but only because we put the `wait`s
in the right places

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```

Deterministic,
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```haskell
p :: Par Det s (IMap Item s Int)
p = do
  cart <- newEmptyMap
  fork $ insert Book 1 cart
  fork $ insert Shoes 1 cart
  return cart

main = do
  putStr $ show $ toList $
    fromIMap $ runParThenFreeze p
```

Deterministic by construction

Freeze After Writing

- LVars
- Quasi-Deterministic

Parallel Programming

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IVars: single writes, blocking (but exact) reads

[Arvind *et al.*, 1989]

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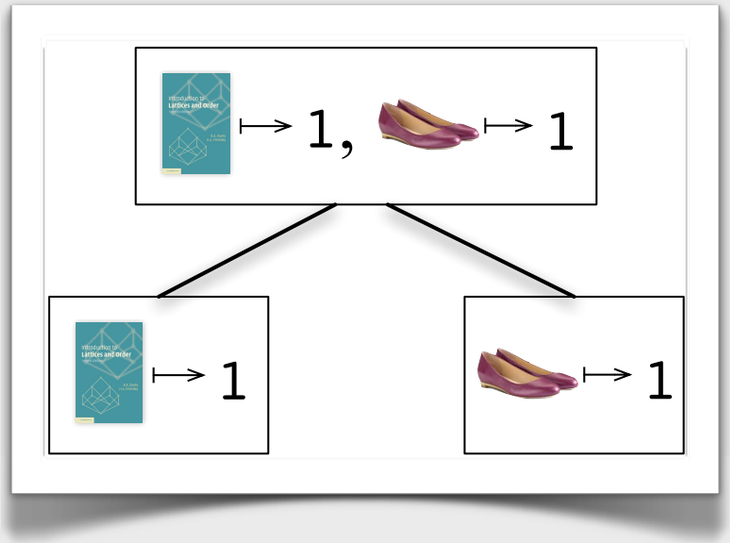

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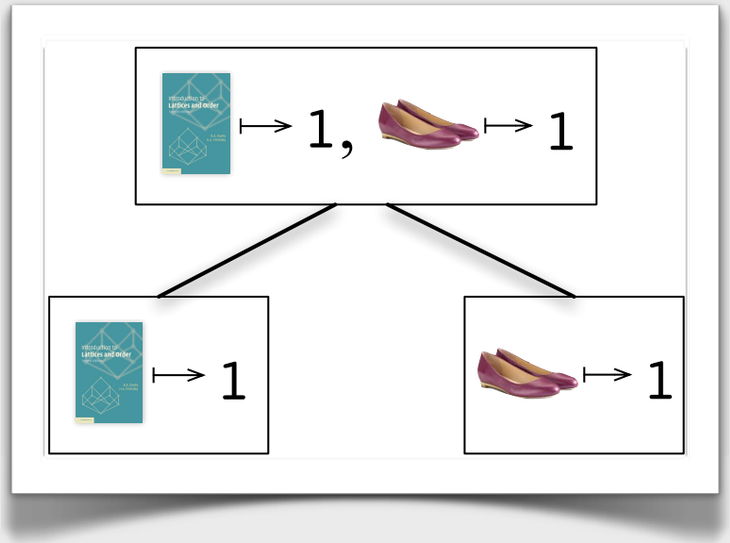
```

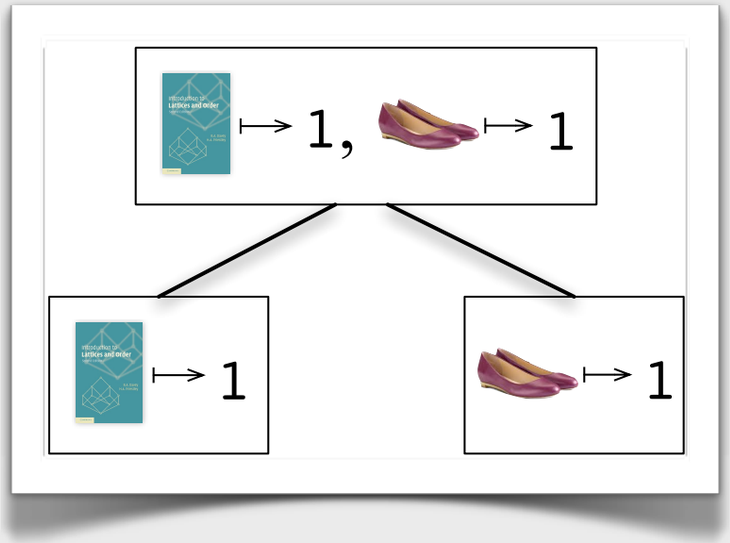


IVars: single writes, blocking (but exact) reads
[Arvind *et al.*, 1989]

LVars: multiple *least-upper-bound* writes, blocking *threshold* reads

```haskell
data Item = Book | Shoes | ...
  deriving (Show, Ord, Eq)

p :: IO (Map Item Int)
p = do cart <- newIORef empty
       async $ atomicModifyIORef cart
         (\m -> (insert Book 1 m, ()))
       async $ atomicModifyIORef cart
         (\m -> (insert Shoes 1 m, ()))
       res <- async $ readIORef cart
       wait res
```

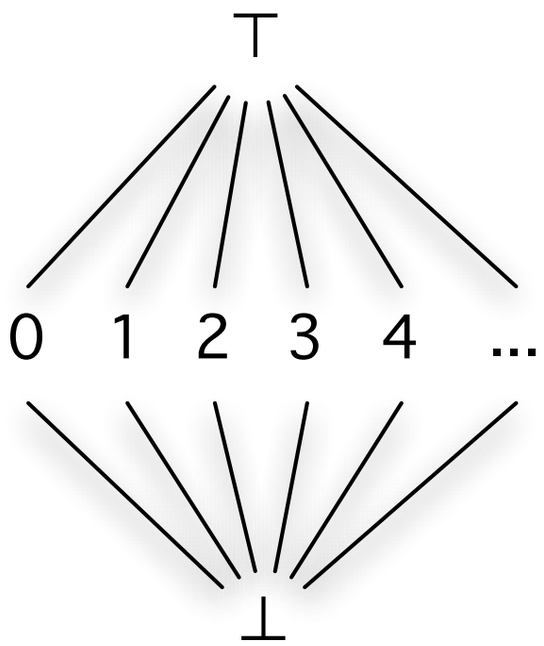


IVars: single writes, blocking (but exact) reads
[Arvind *et al.*, 1989]

LVars: multiple *least-upper-bound* writes, blocking *threshold* reads

* actually a bounded join-semilattice

num

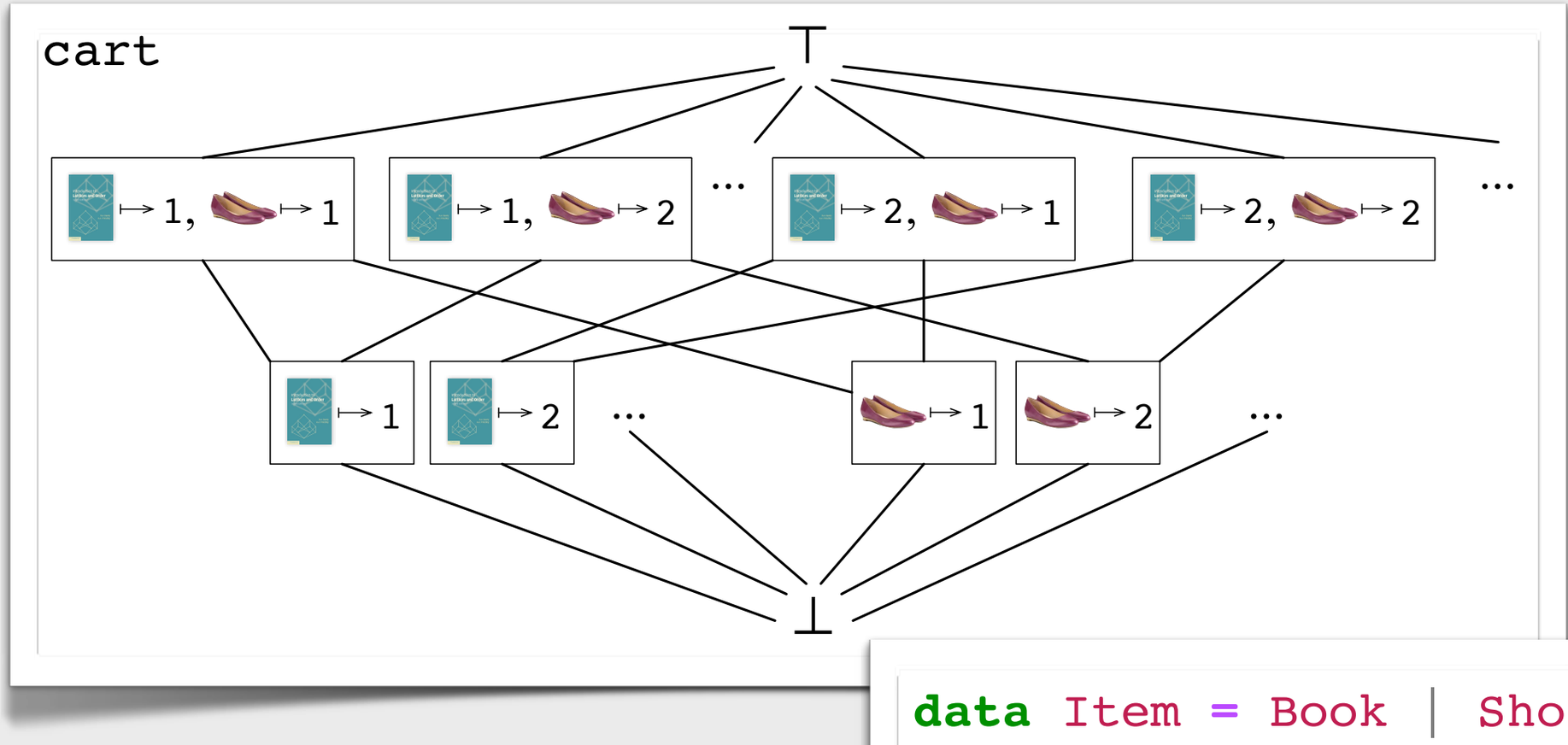


Raises an error, since 3 ⊔ 4 = ⊤

```
do
   fork (put num 3)
   fork (put num 4)
```

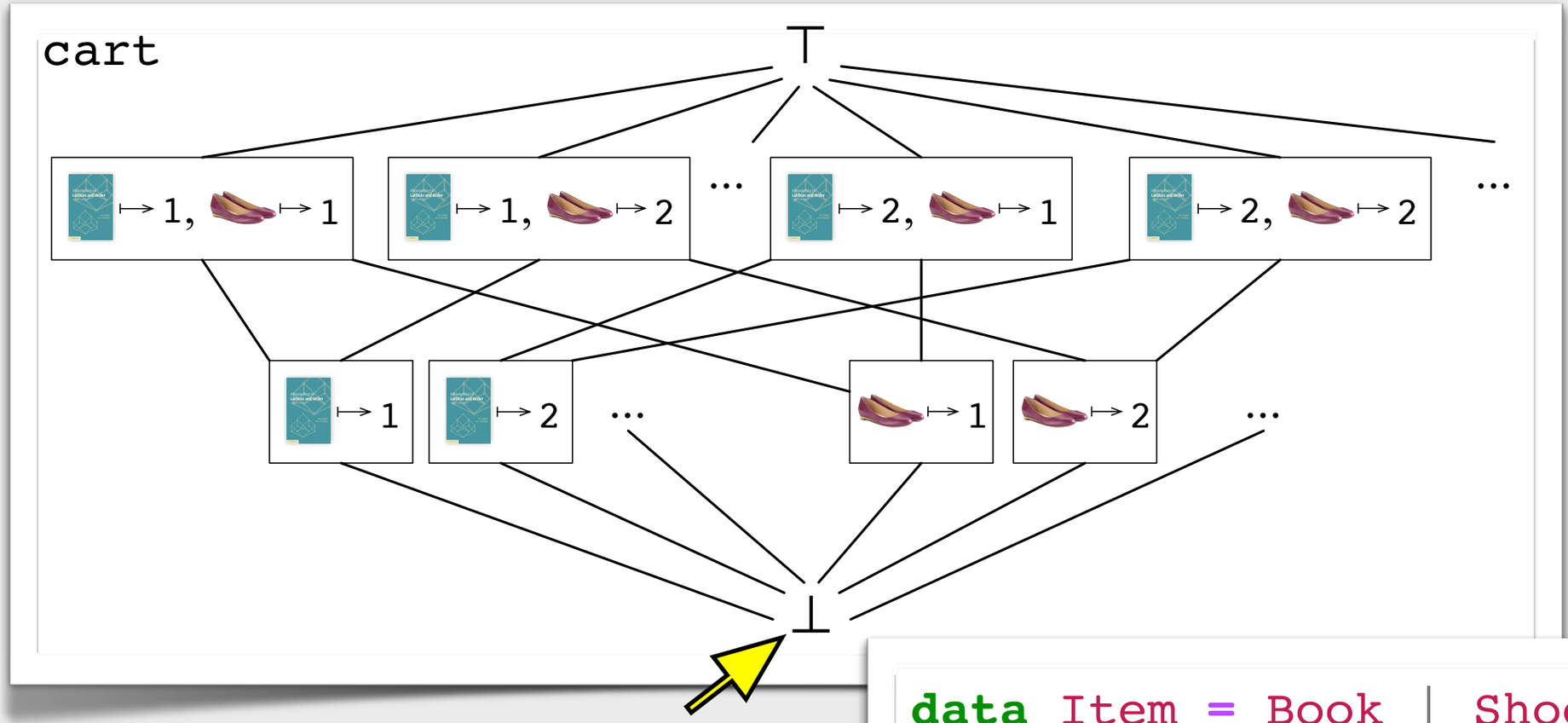
Works fine, since 4 ⊔ 4 = 4

```
do
   fork (put num 4)
   fork (put num 4)
```




```haskell
data Item = Book | Shoes
  deriving (Show, Ord, Eq)

p = do
  cart <- newEmptyMap
  fork $ insert Shoes 1 cart
  fork $ insert Book 2 cart
  getKey Book cart -- returns 2
```

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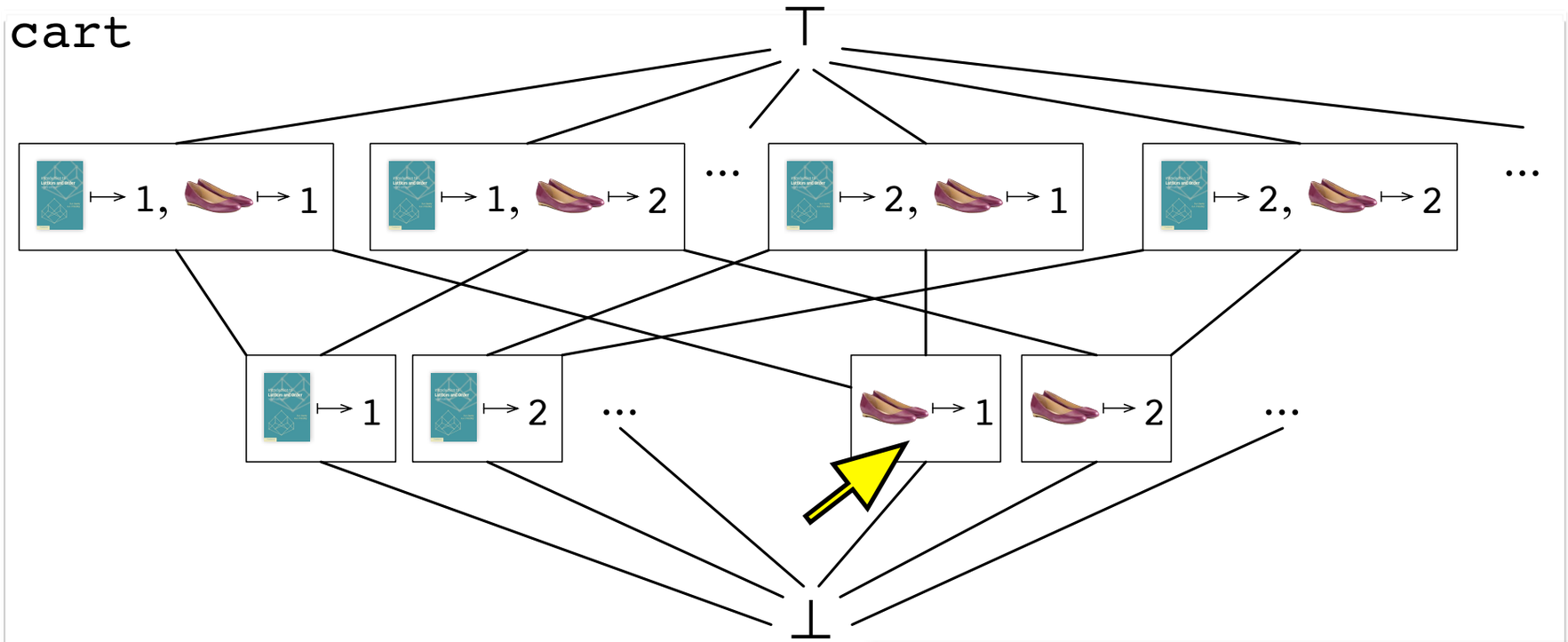


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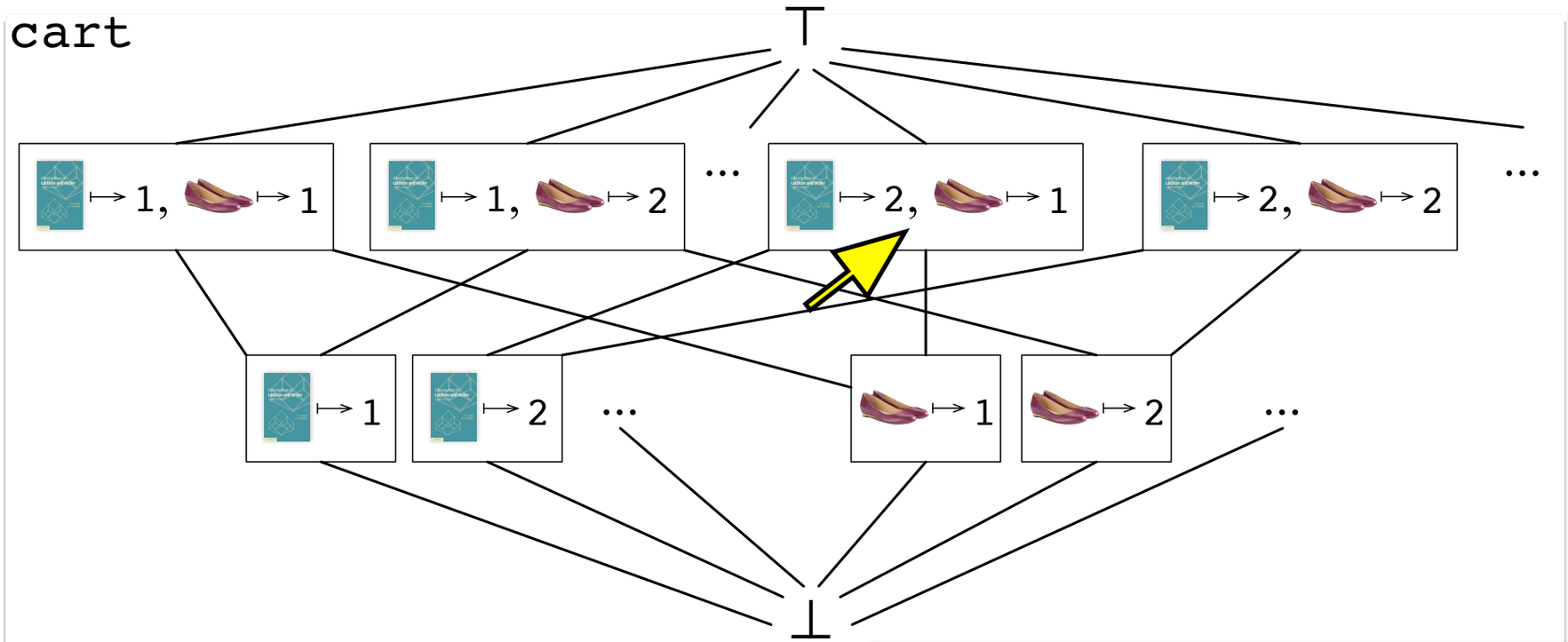


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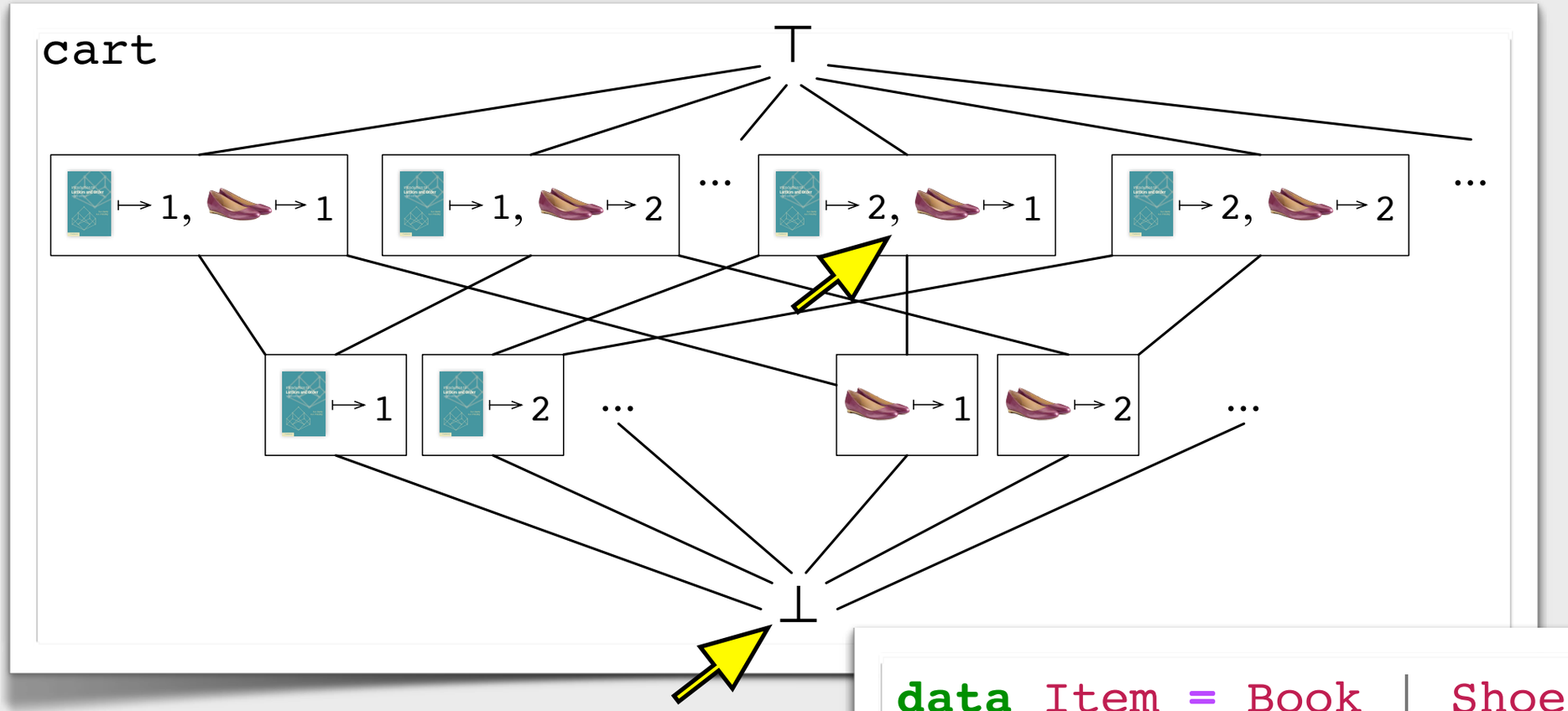


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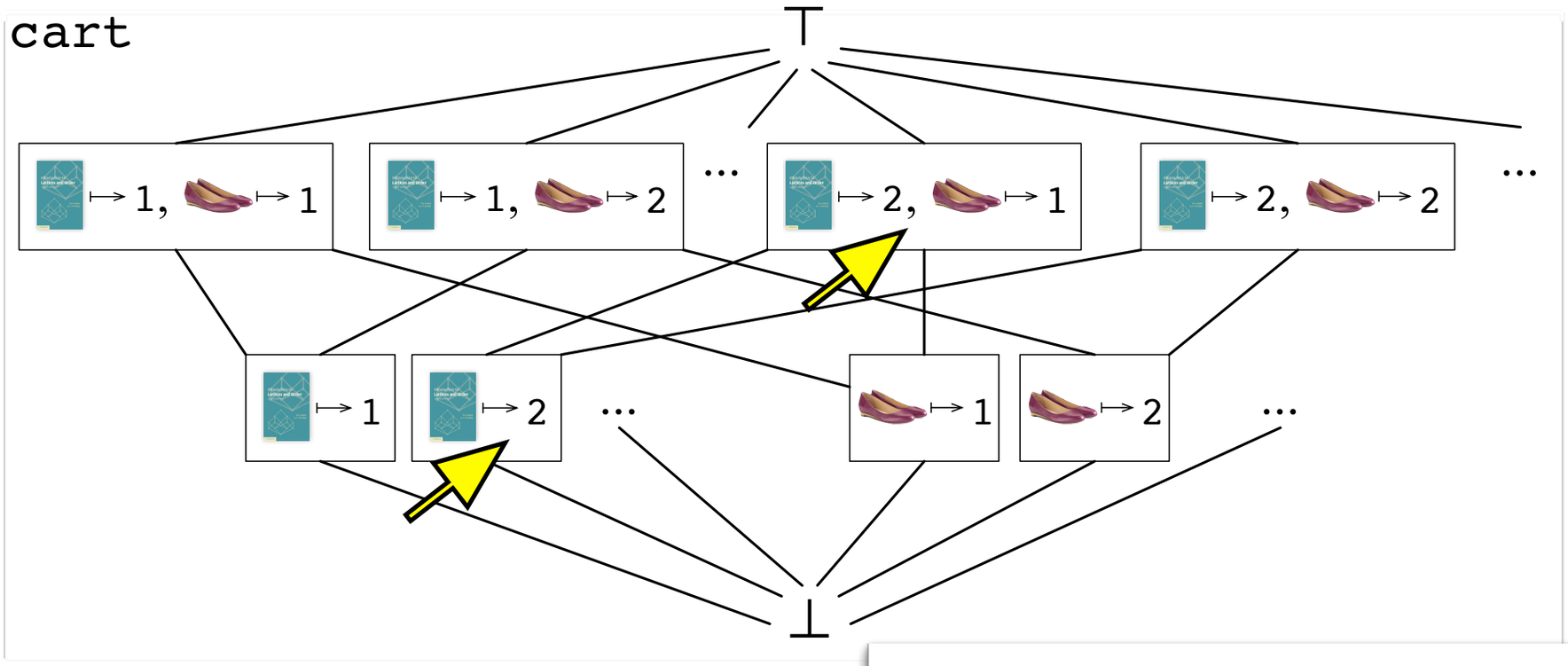


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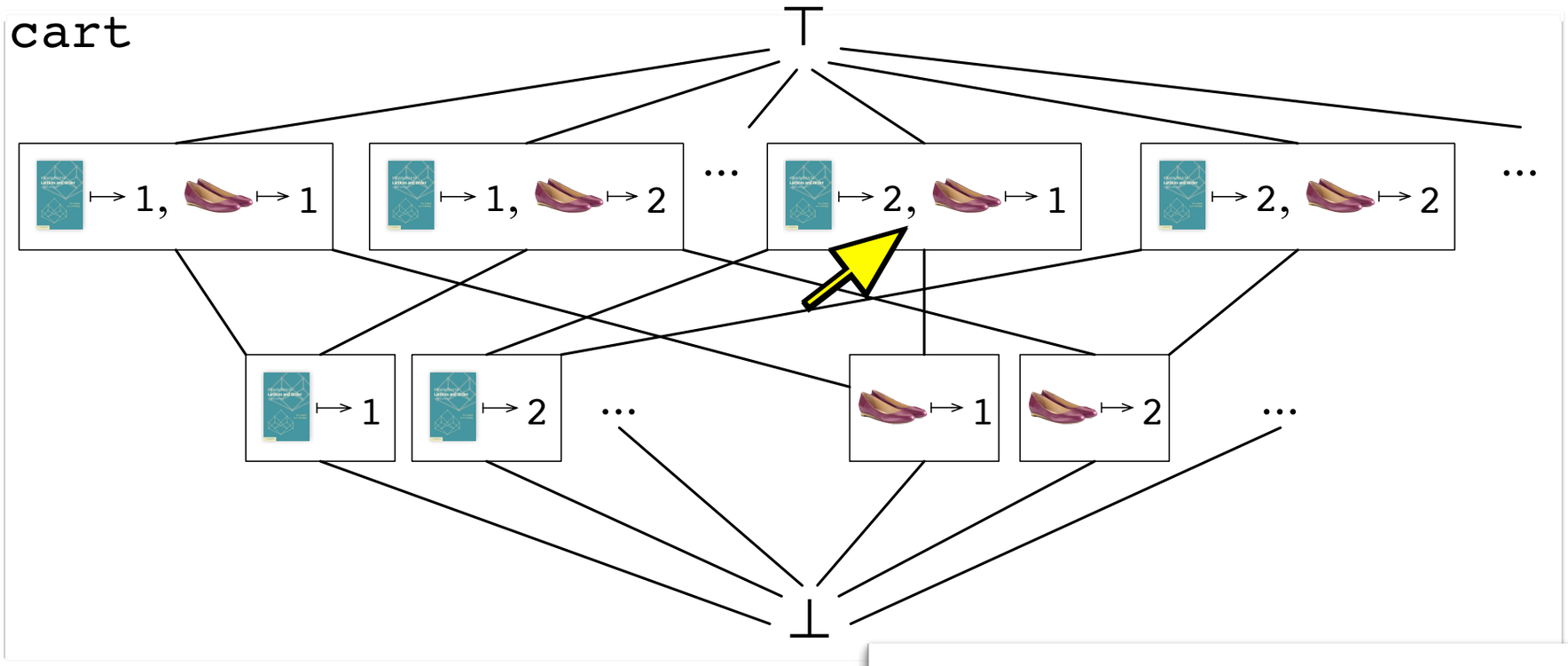


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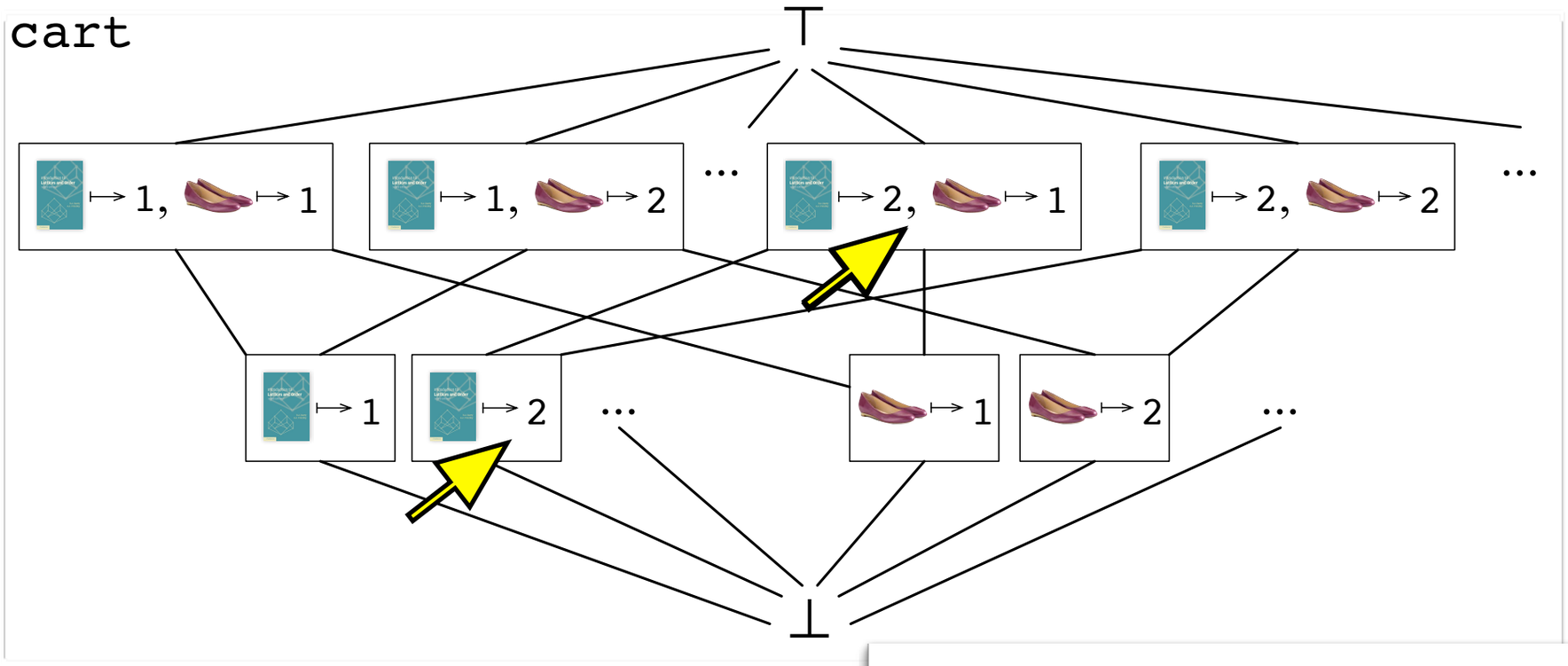


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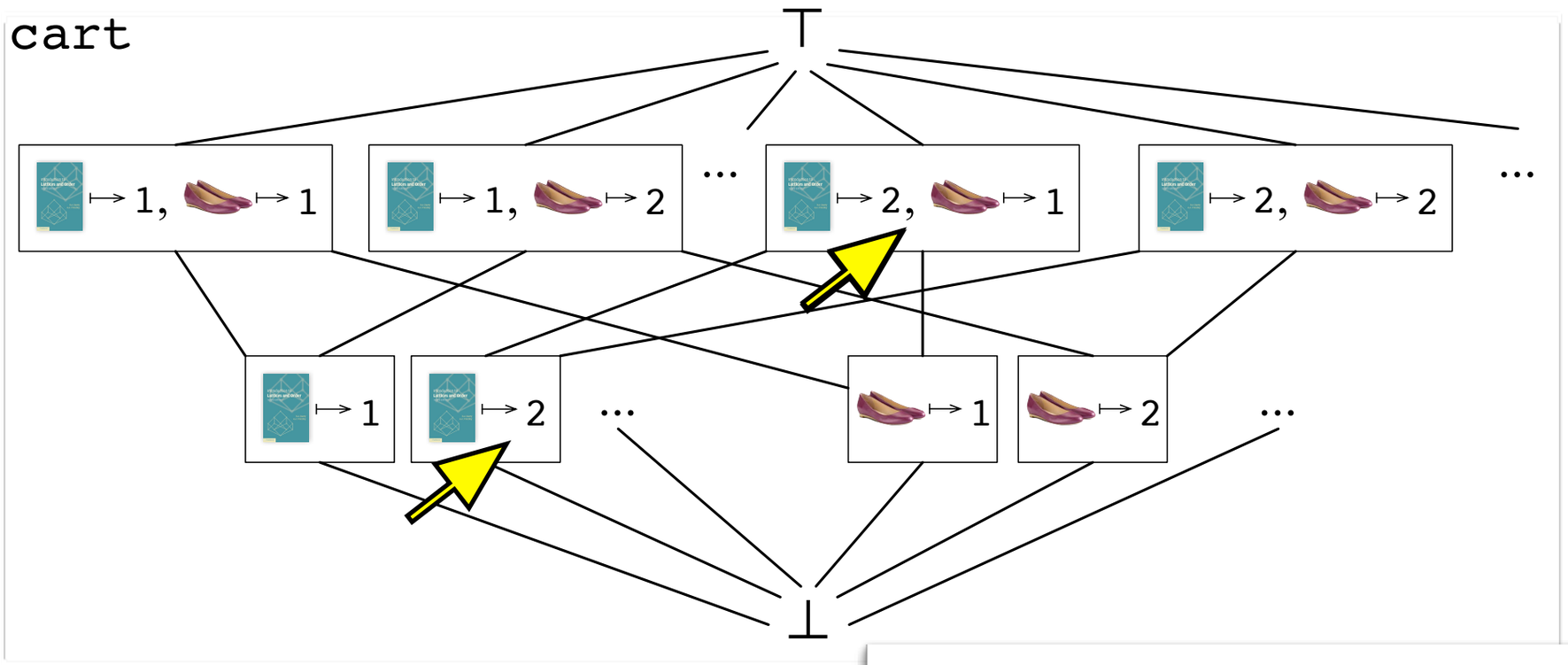


```
{(Book,1), (Book,2), ...}
```

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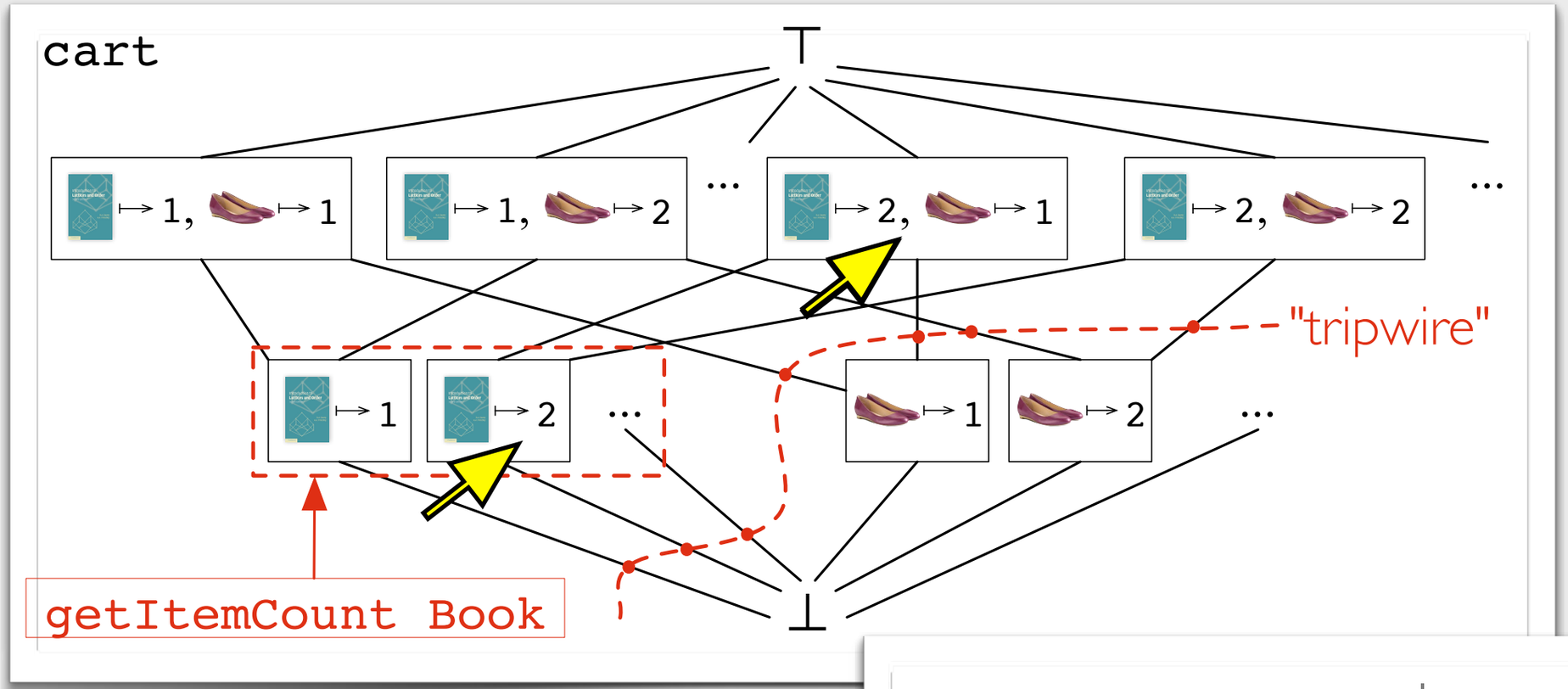


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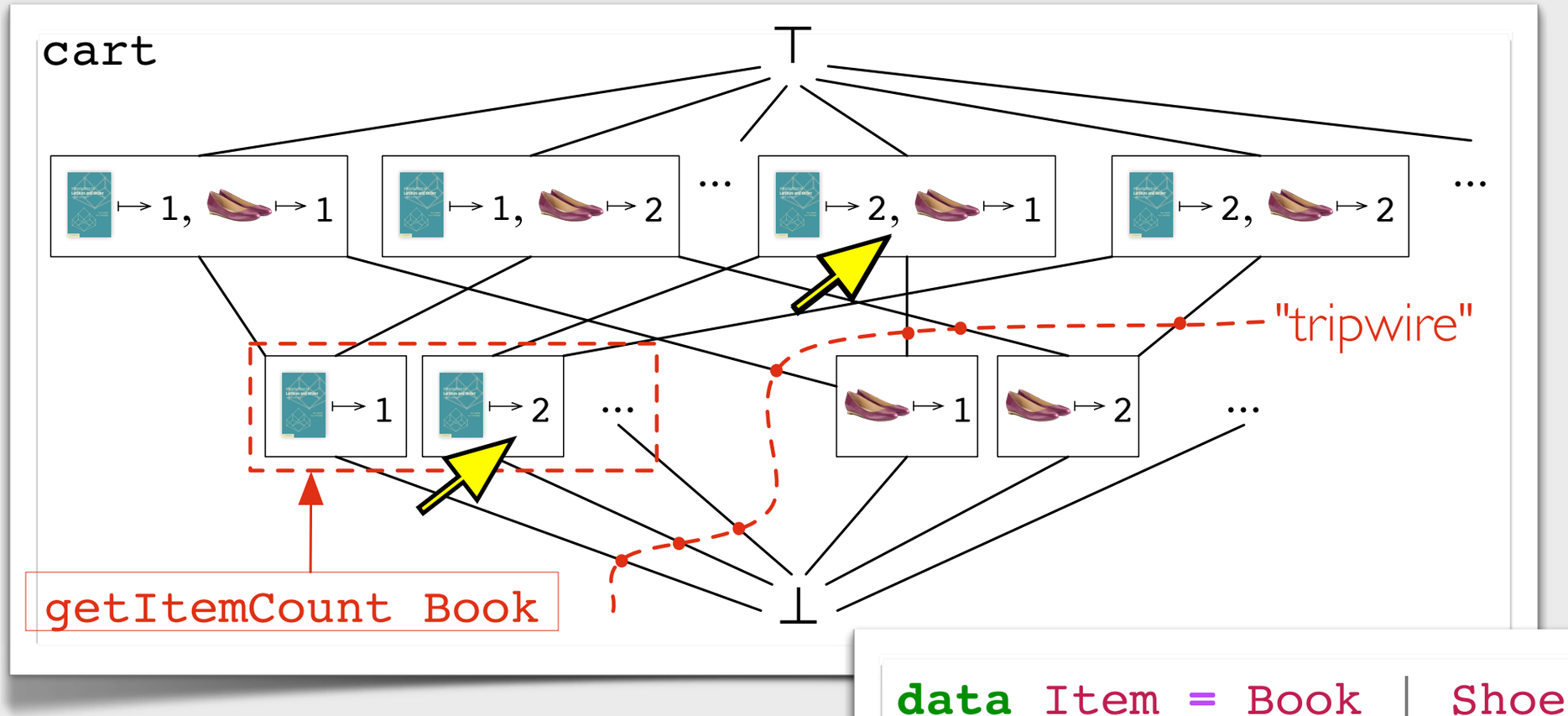


```
{(Book,1), (Book,2), ...}
```

The threshold set must be *pairwise incompatible*

```haskell
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p = do
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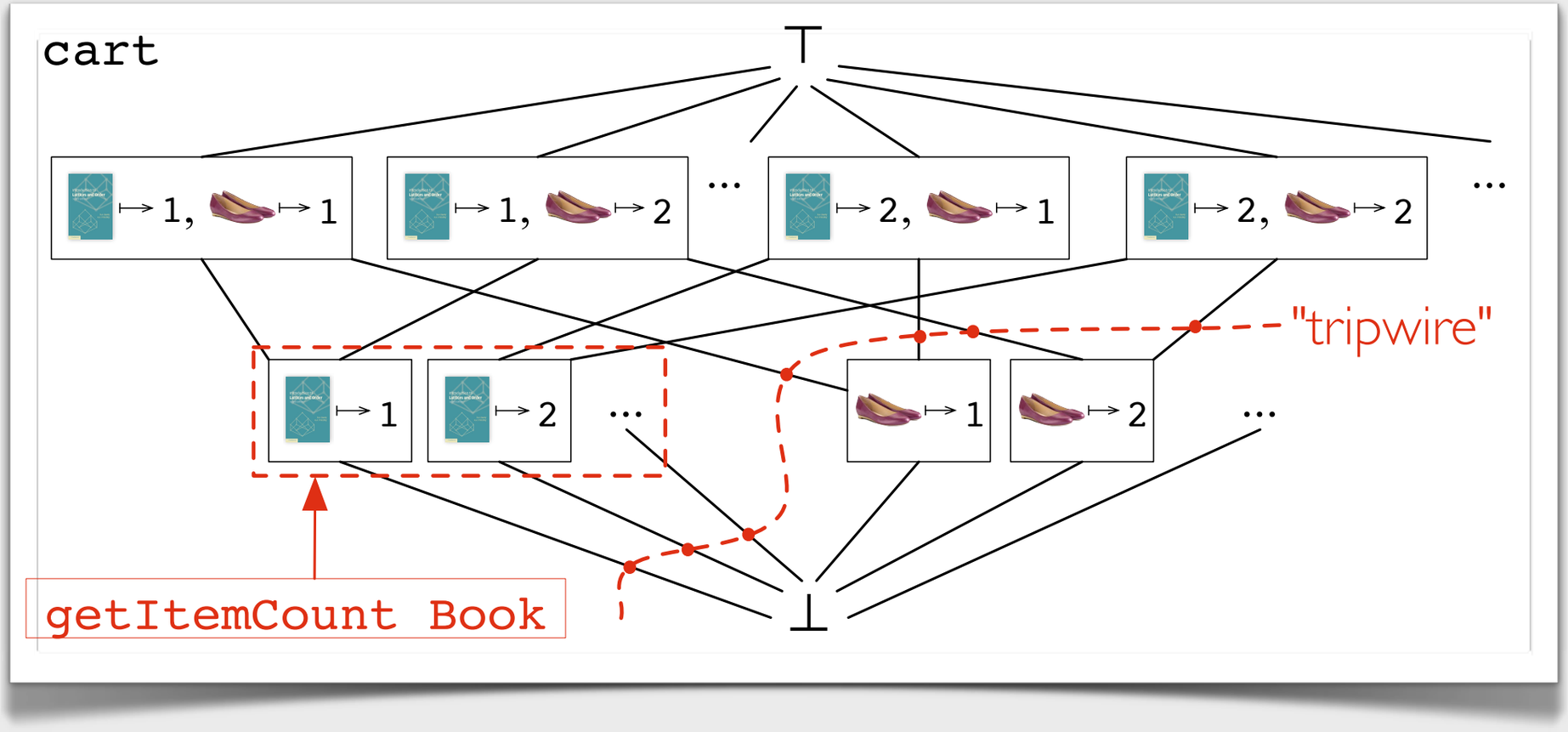
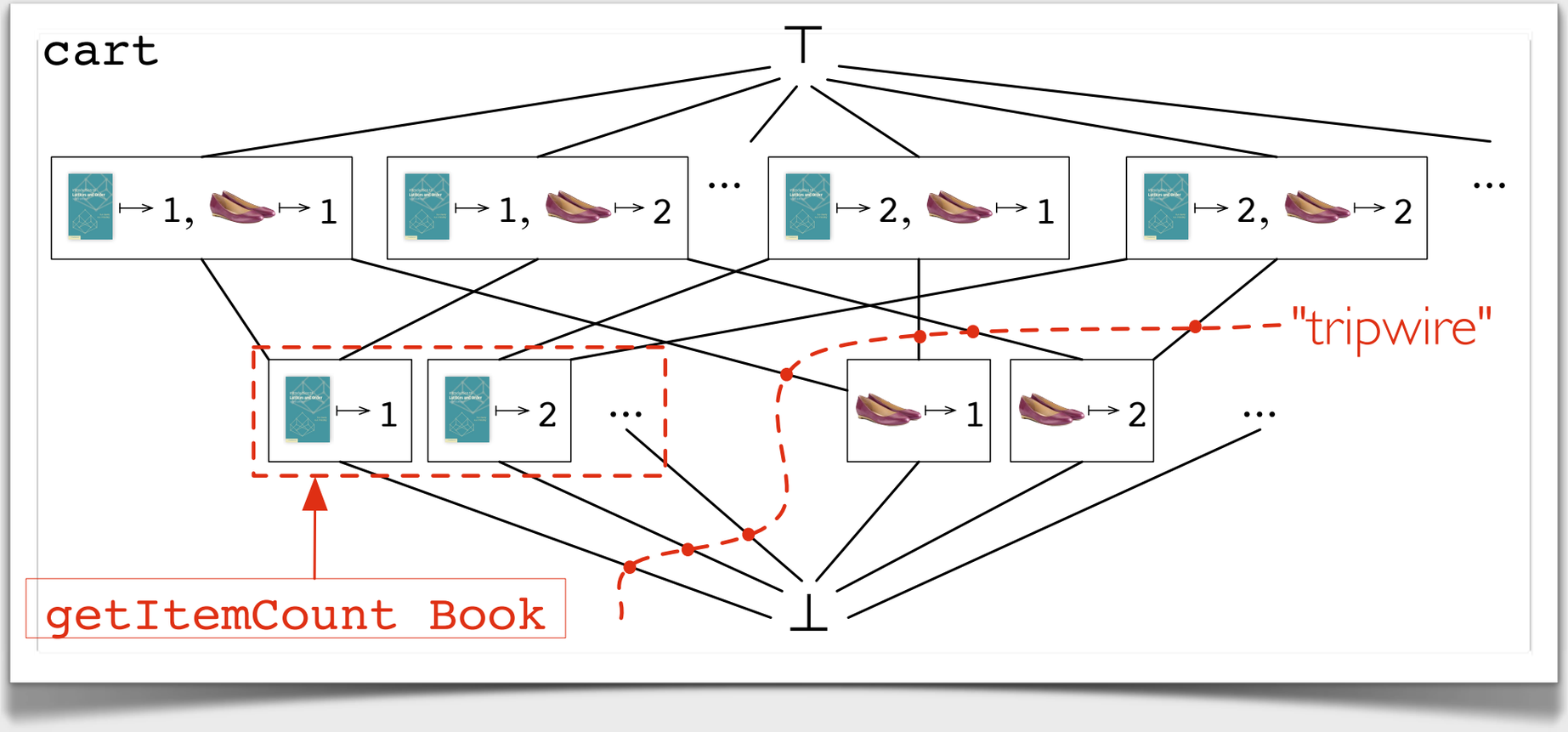
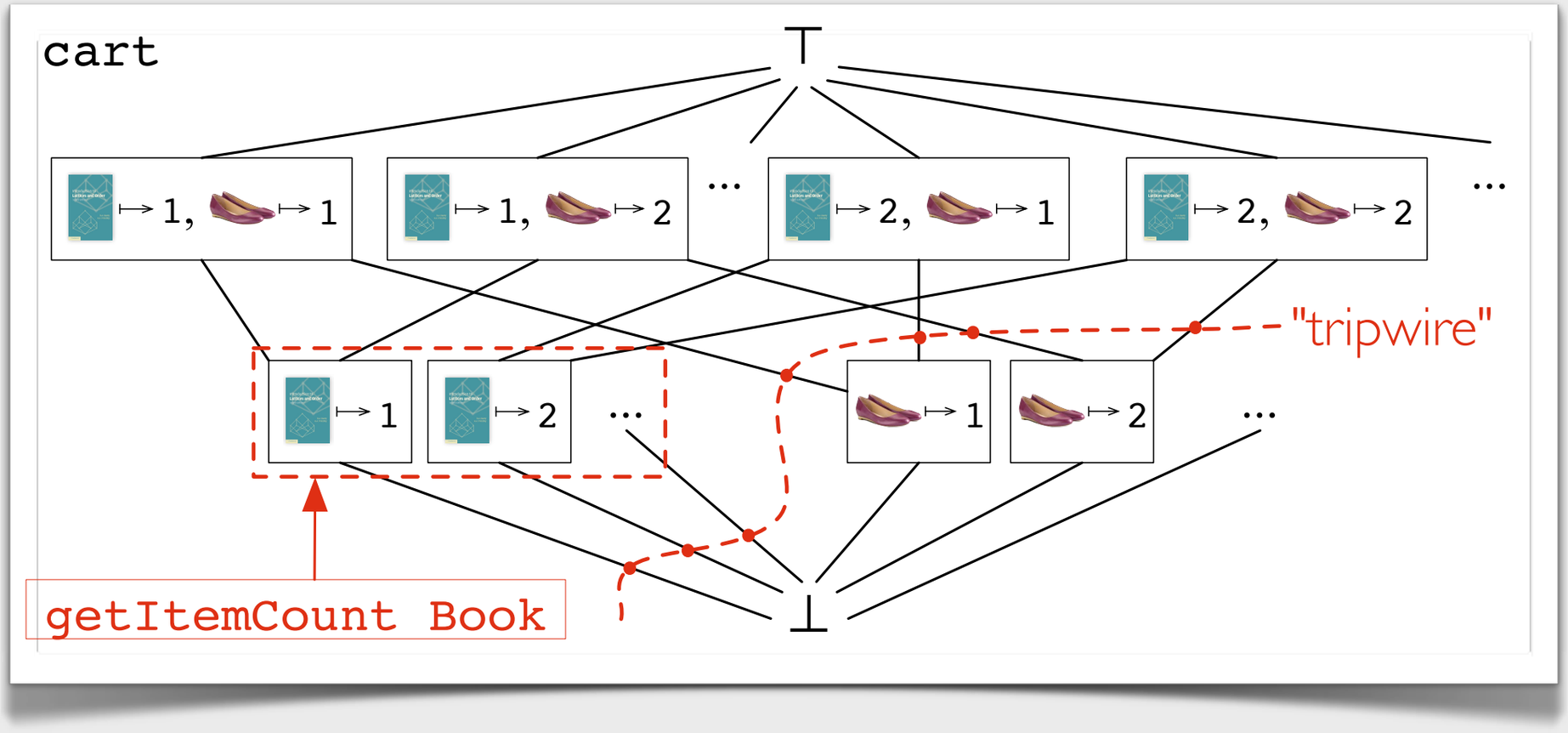


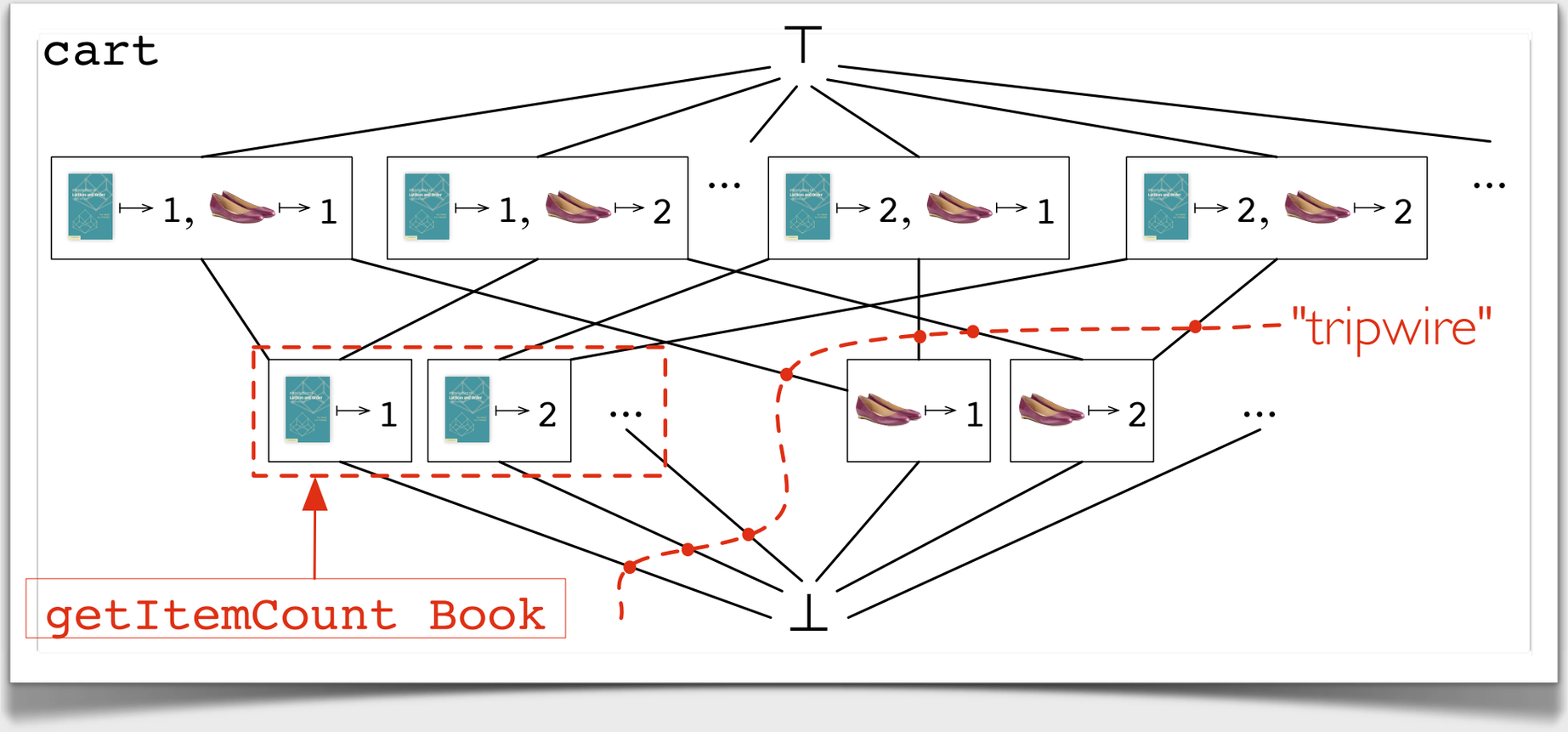
✖ Can't see the exact, complete contents of the cart



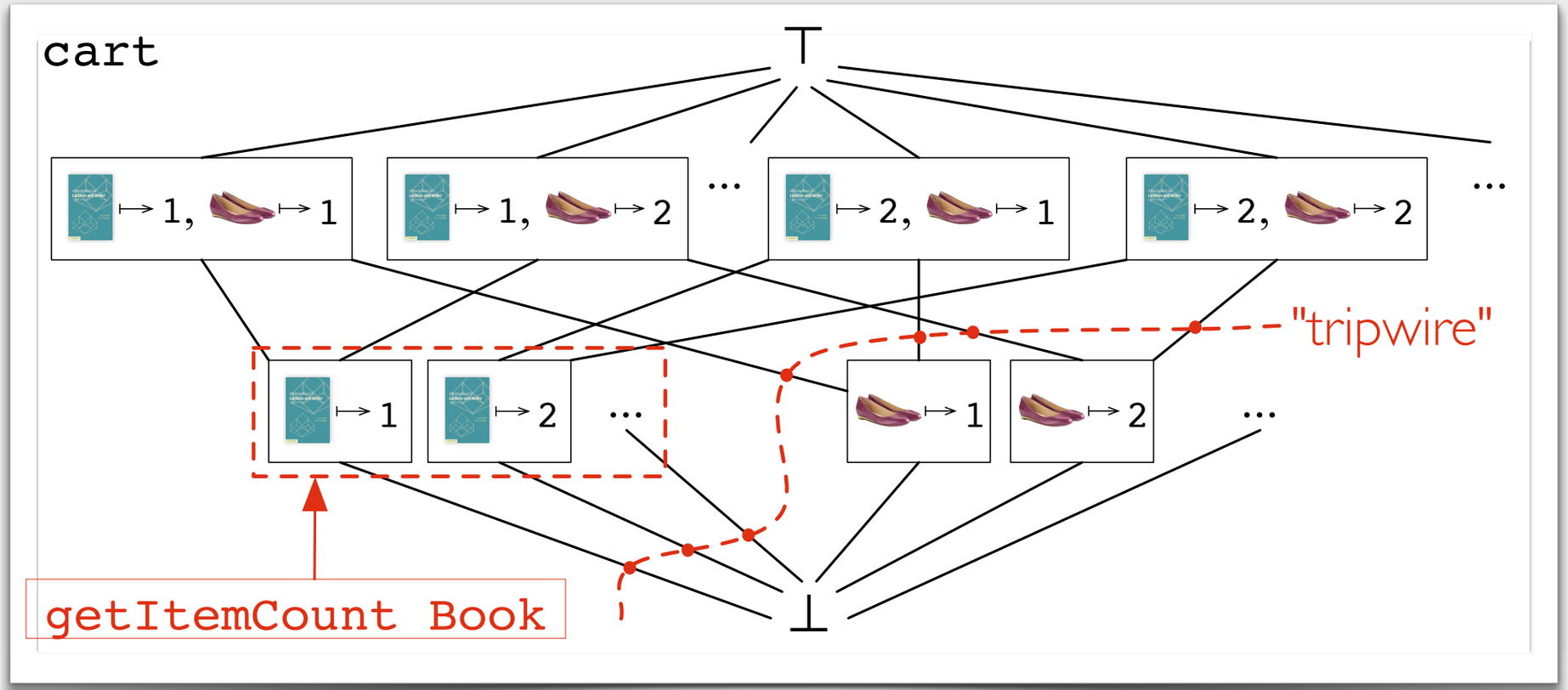
- ✗ Can't see the exact, complete contents of the cart
- ✗ Can't iterate over the items in the cart



- ✗ Can't see the exact, complete contents of the cart
- ✗ Can't iterate over the items in the cart
- ✗ Can't determine if an item *isn't* in the cart



- ✗ Can't see the exact, complete contents of the cart
- ✗ Can't iterate over the items in the cart
- ✗ Can't determine if an item *isn't* in the cart
- ✗ Can't react to writes that we weren't expecting



- ✓ Can see the exact, complete contents of the cart
- ✓ Can iterate over the items in the cart
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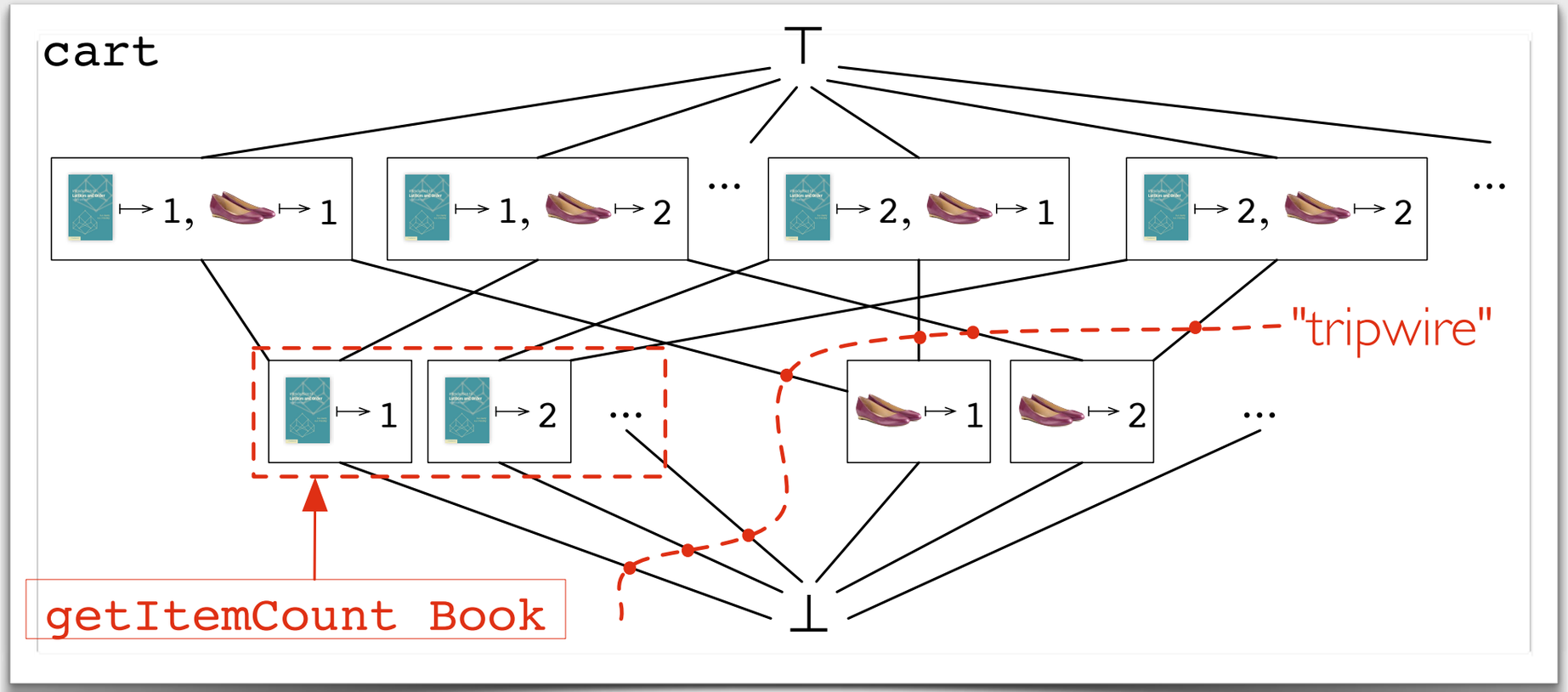


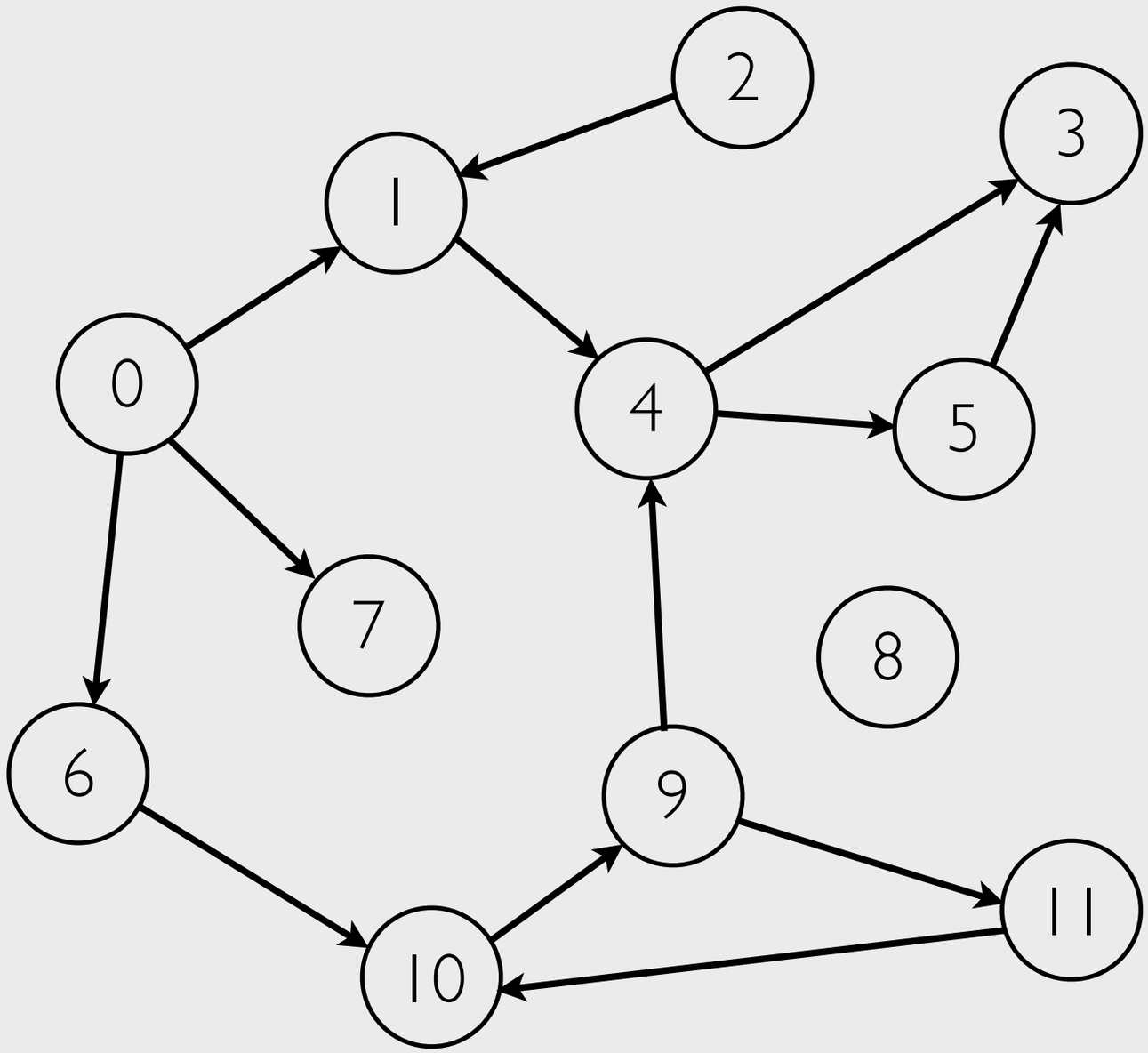
- ✓ Can see the exact, complete contents of the cart
- ✓ Can iterate over the items in the cart
- ✓ Can determine if an item *isn't* in the cart
- ✓ Can react to writes that we weren't expecting

} handlers, quiescence, freezing

Freeze After Writing

- LVars
- Quasi-Deterministic

Parallel Programming



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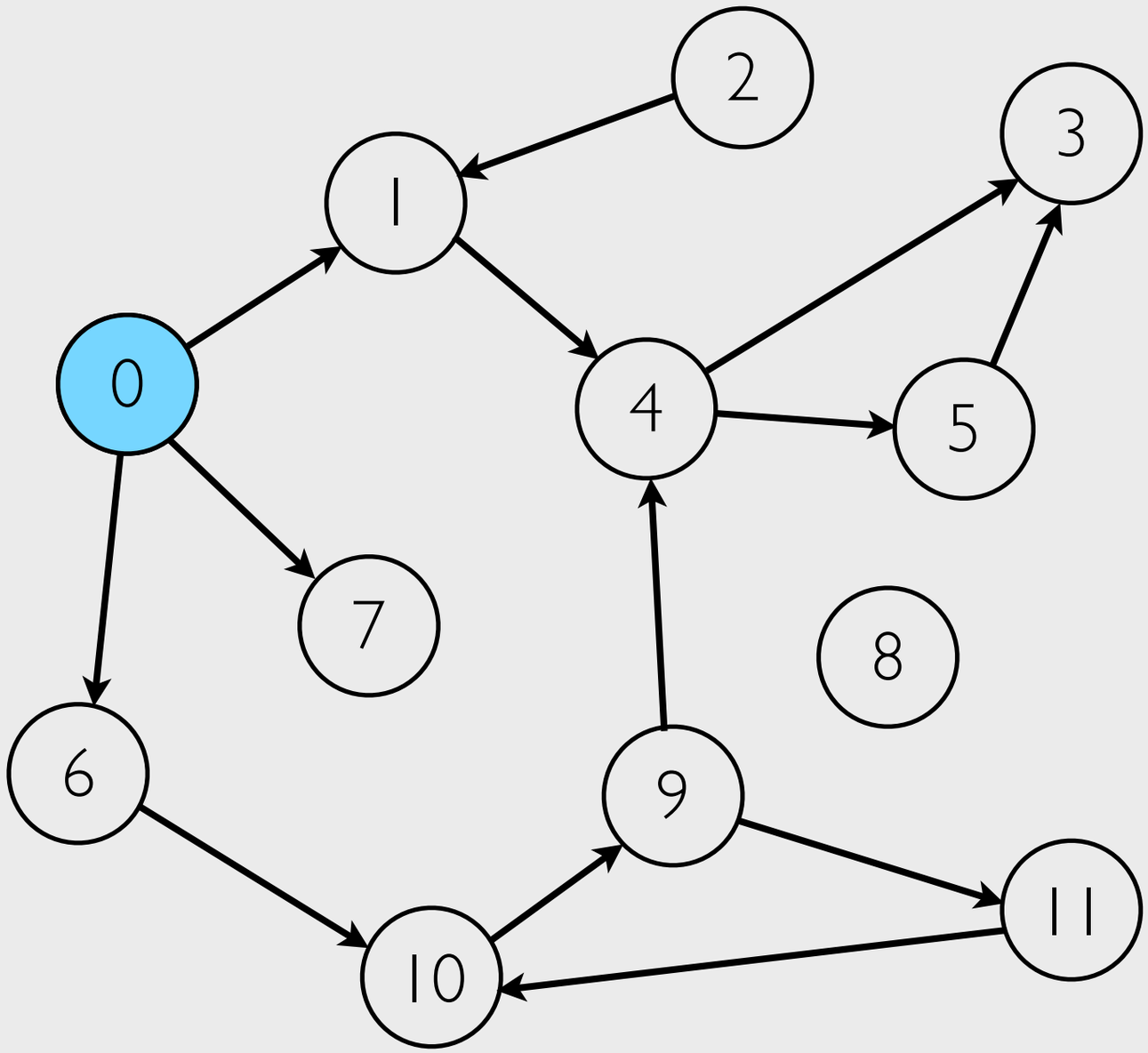

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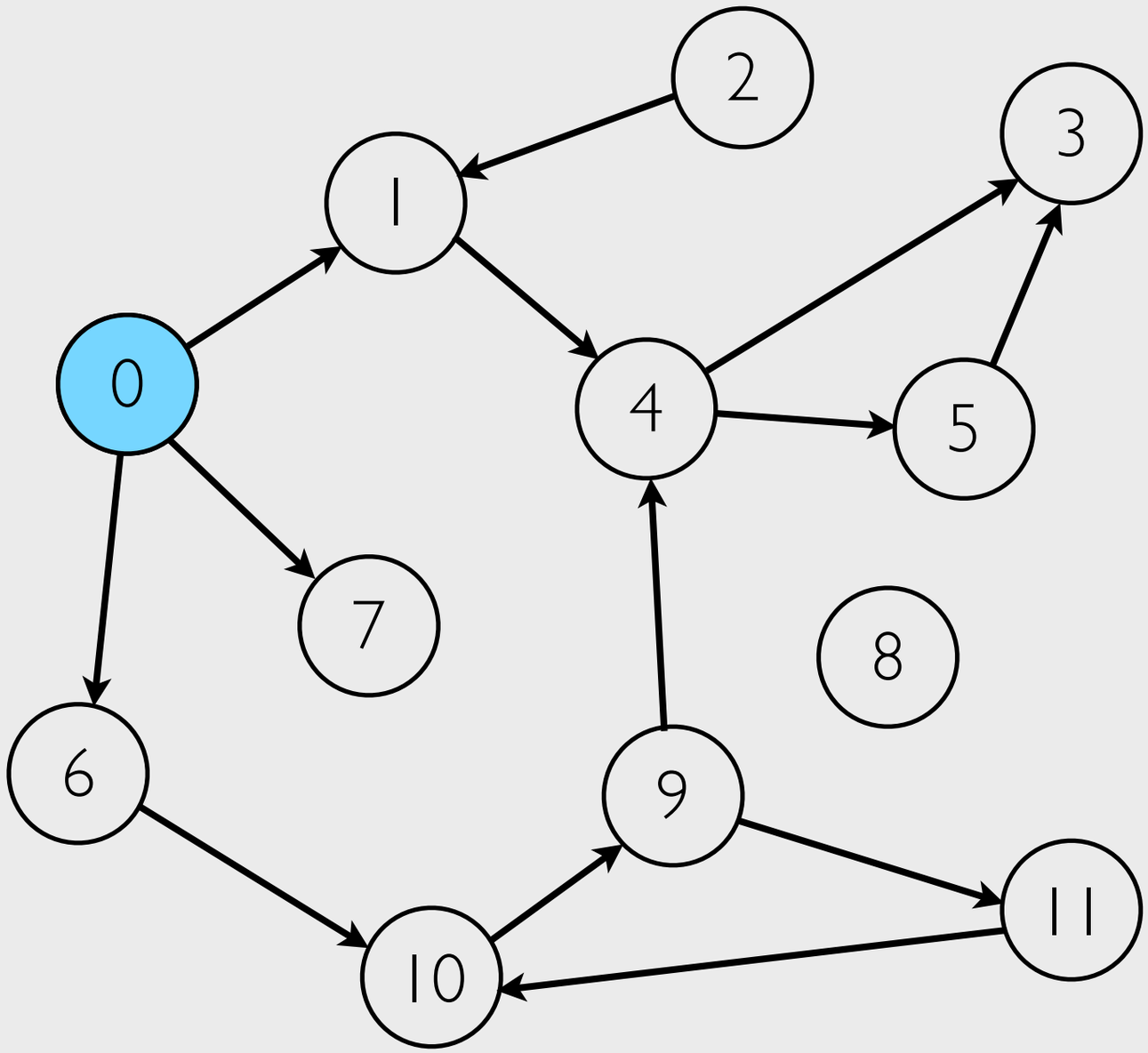

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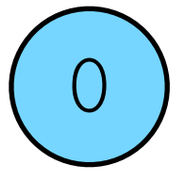

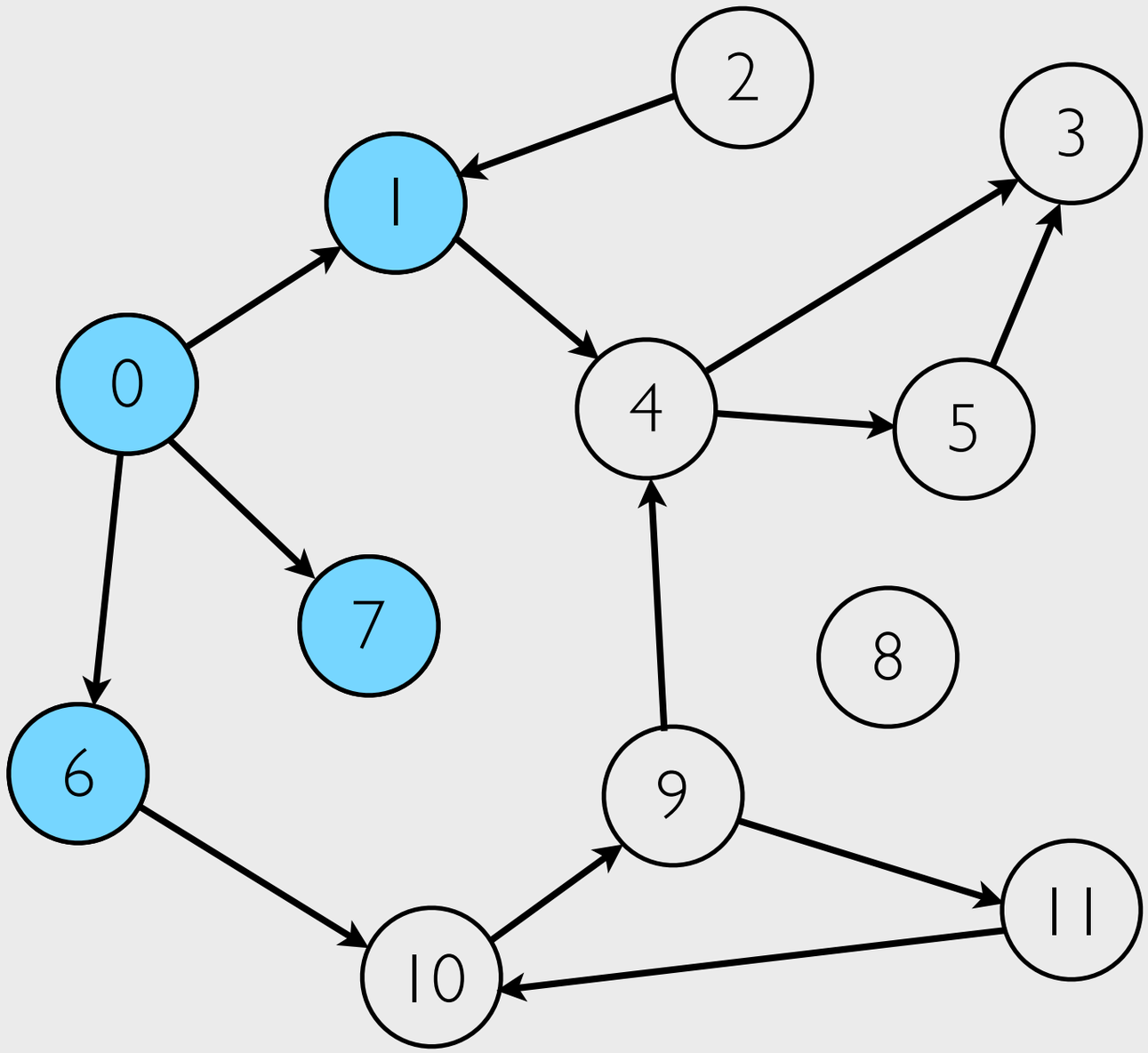

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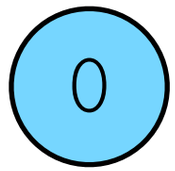

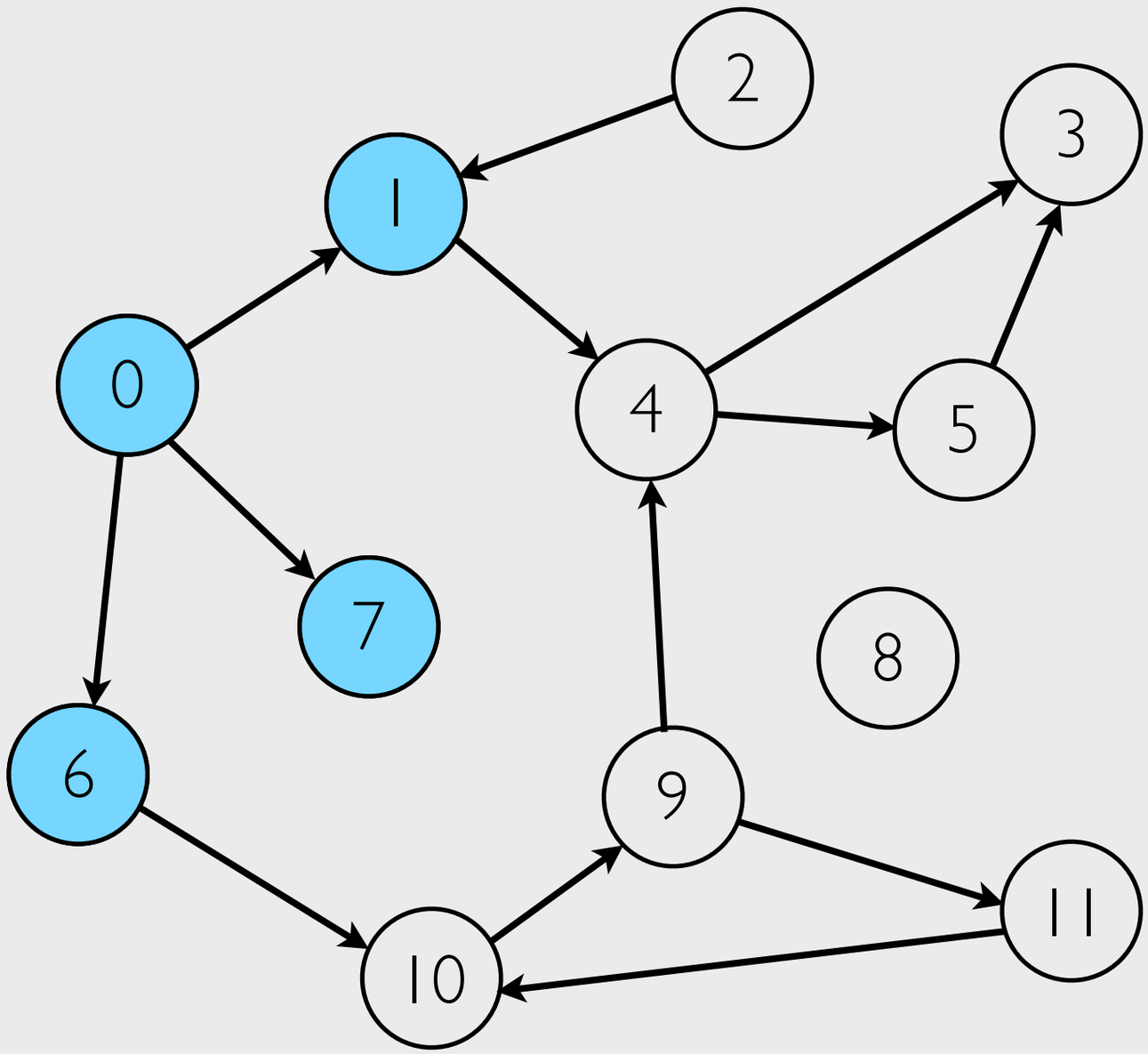

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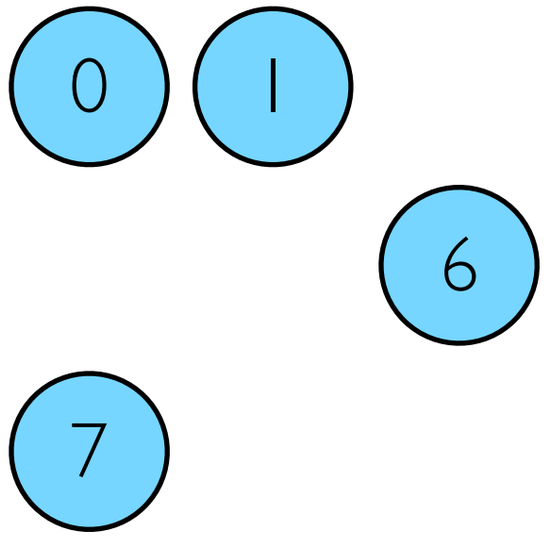

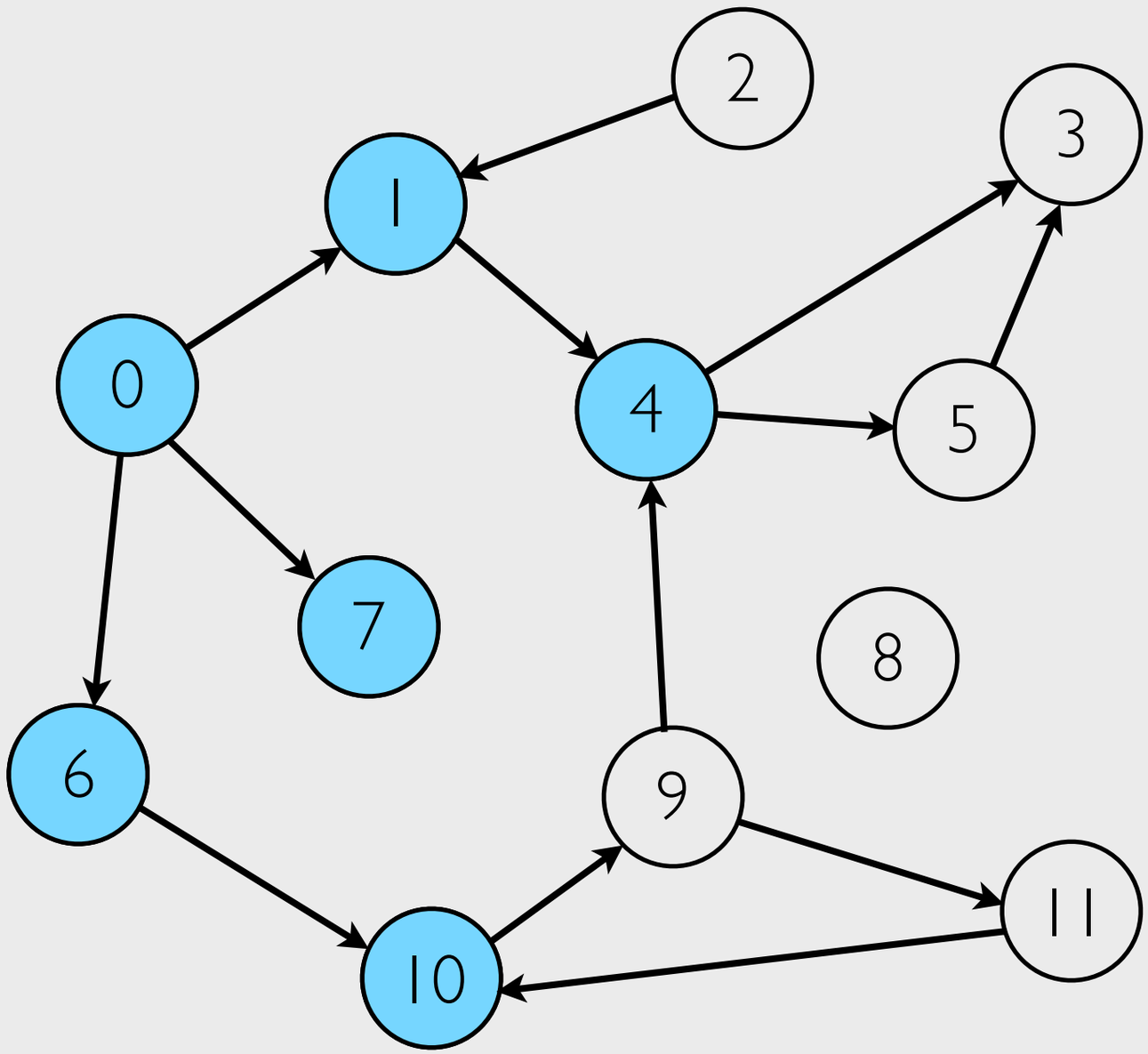
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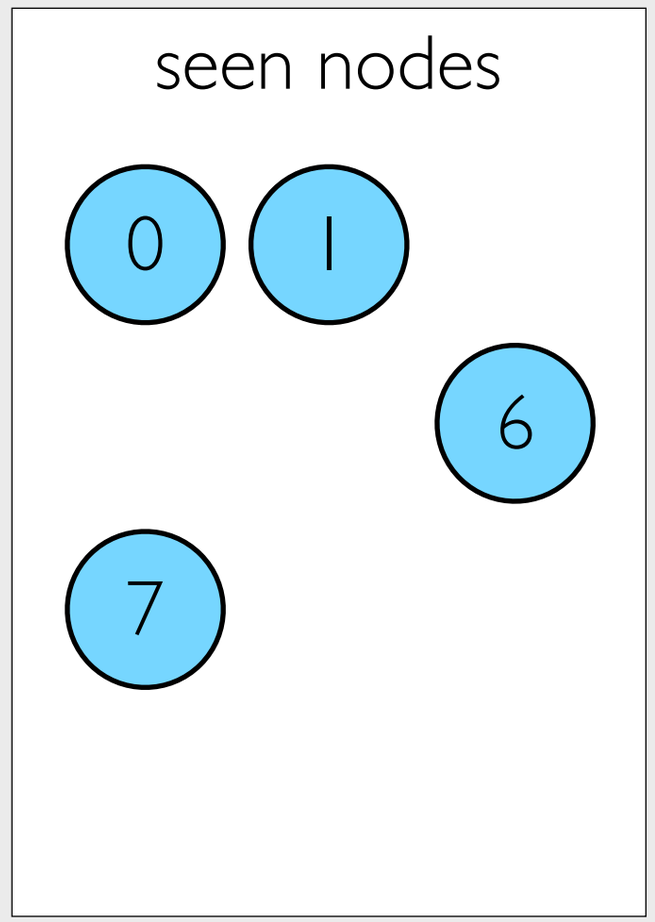
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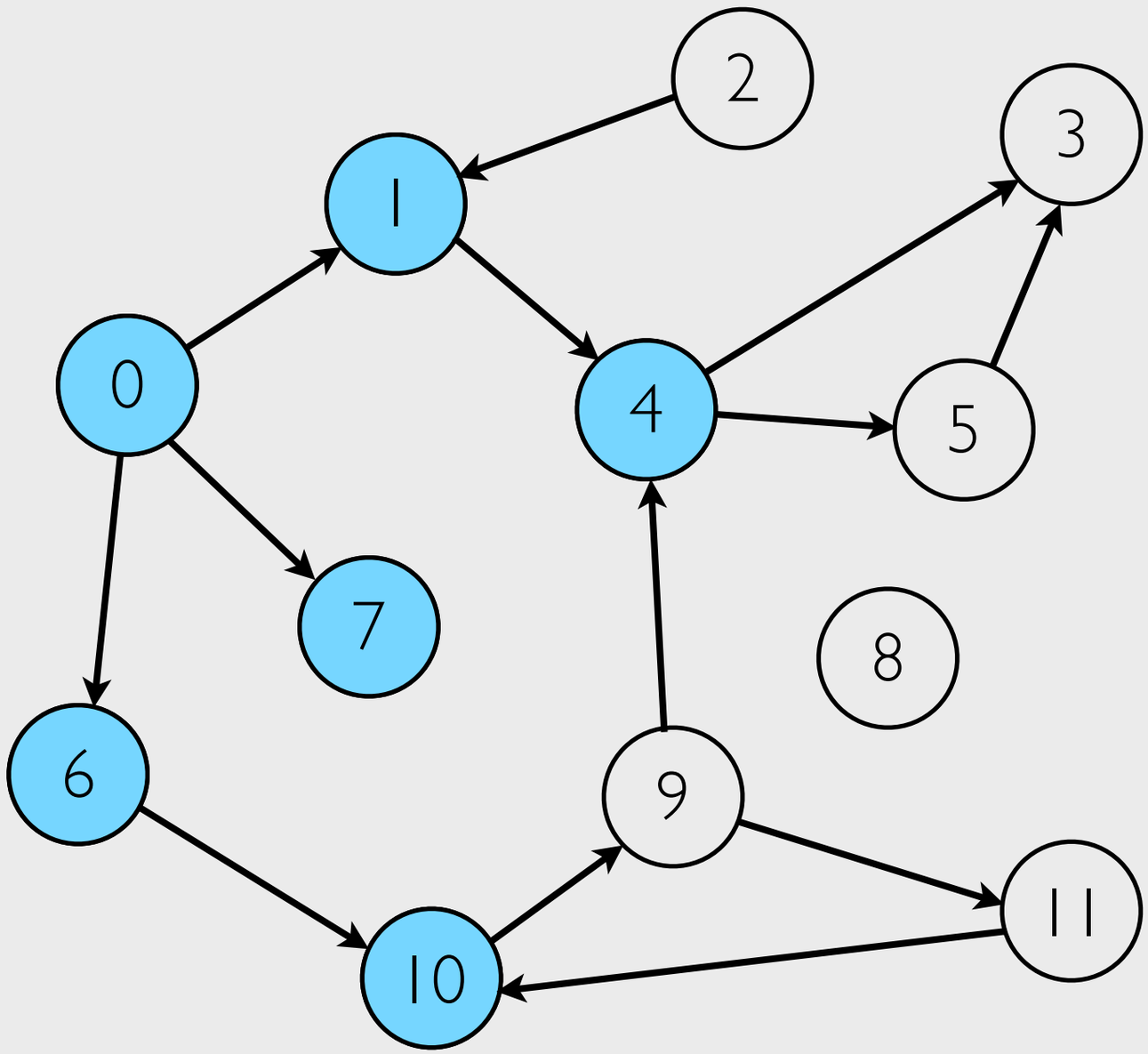

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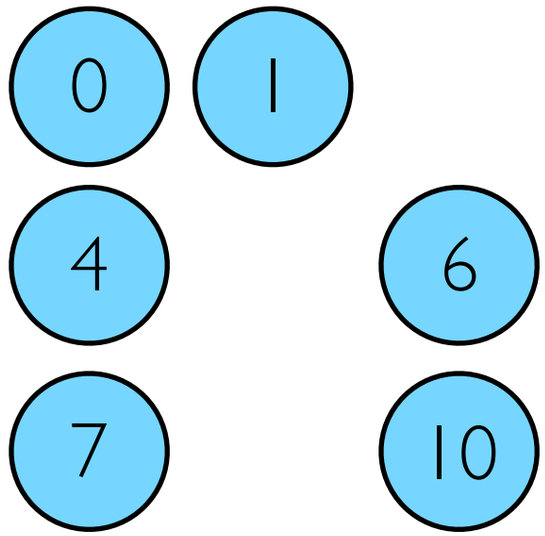

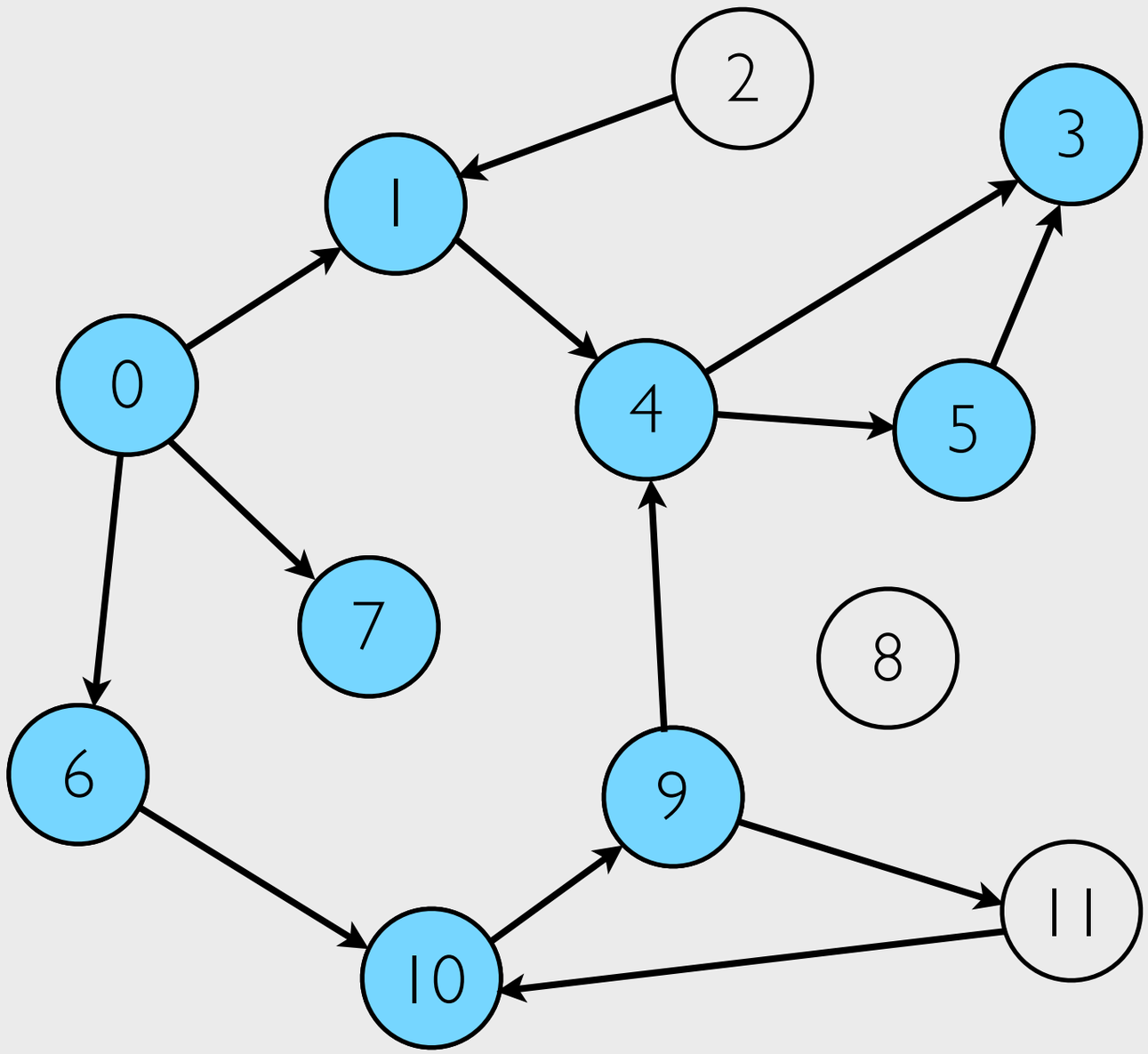

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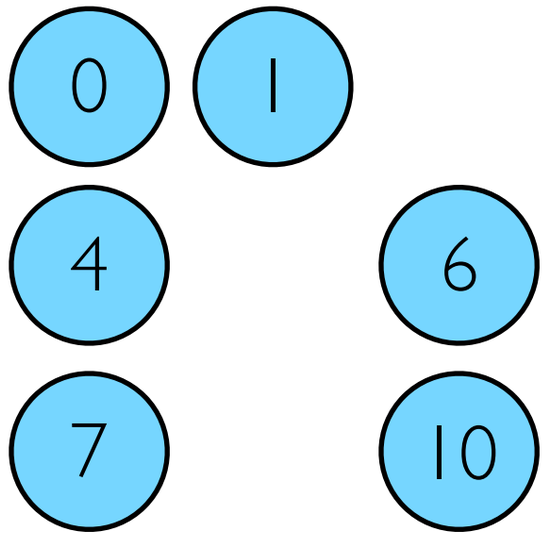

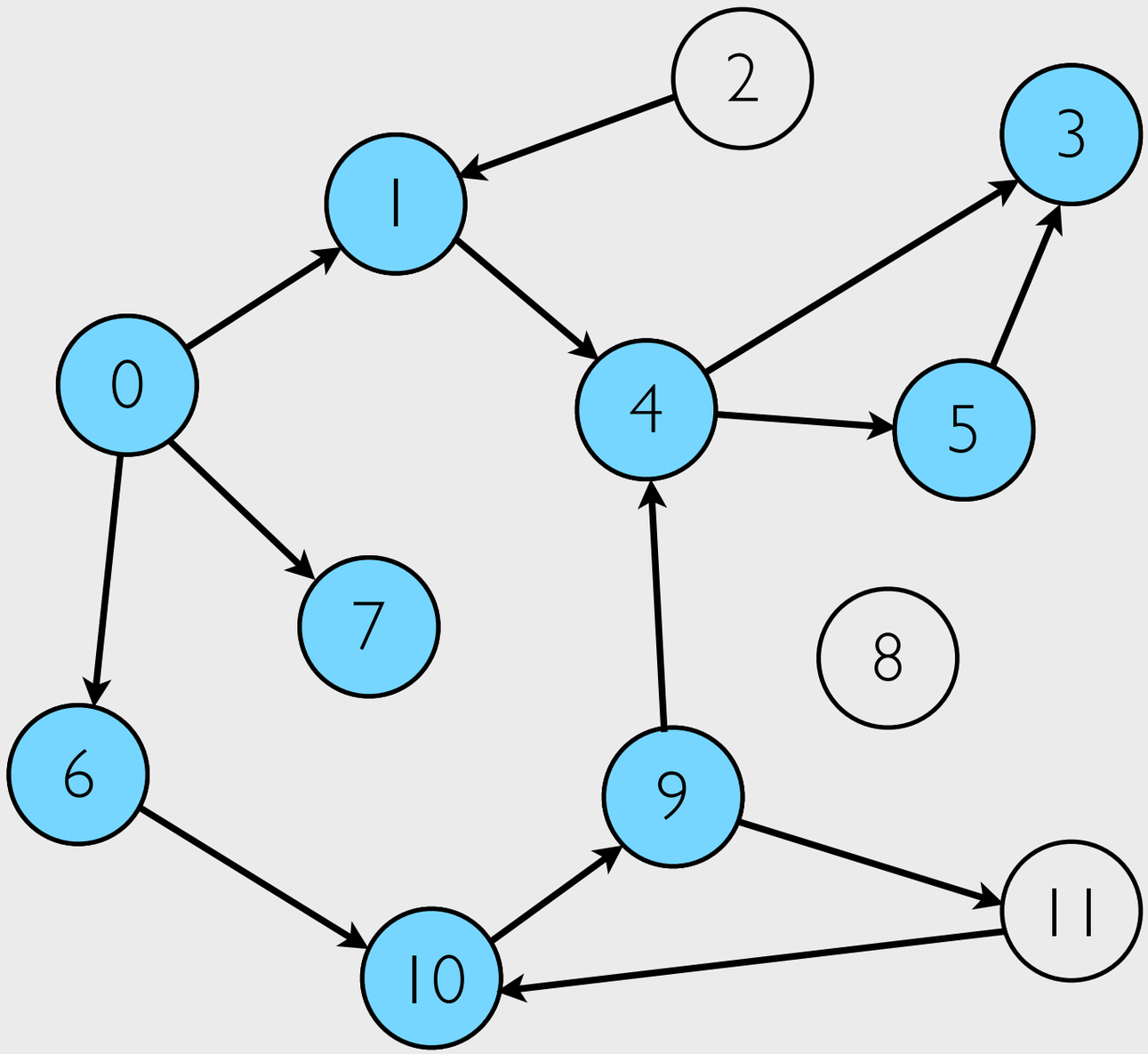

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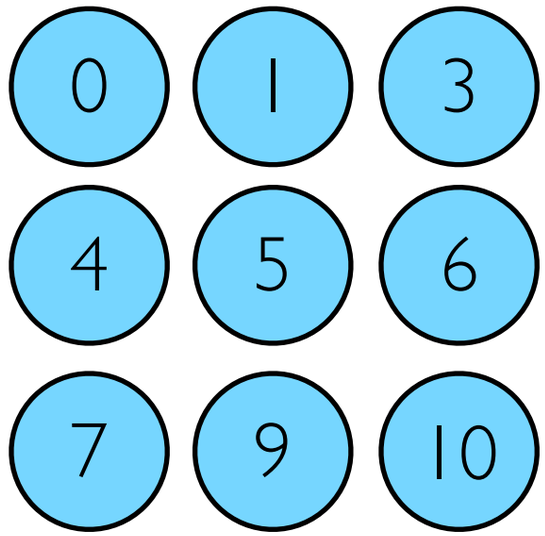

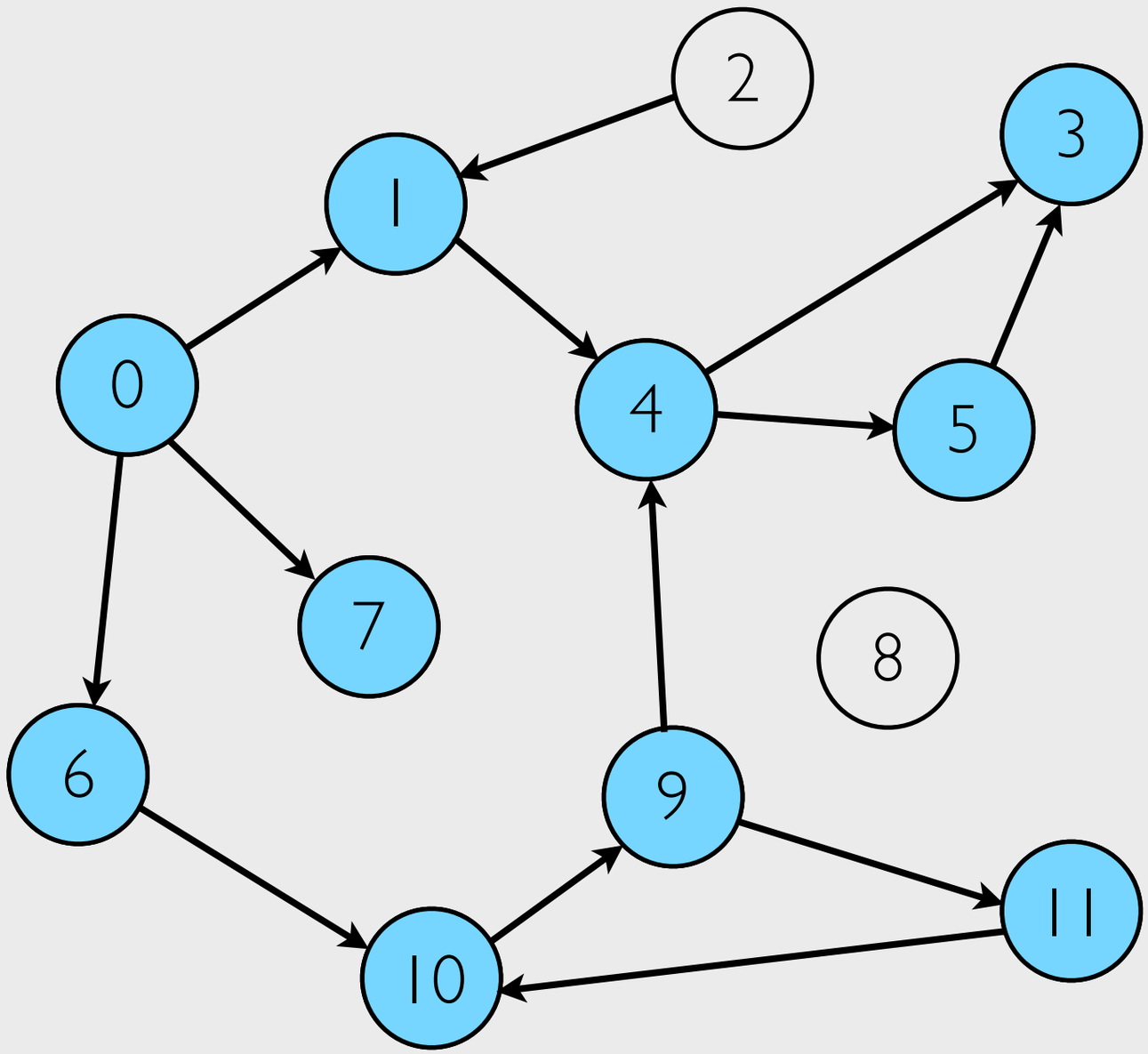

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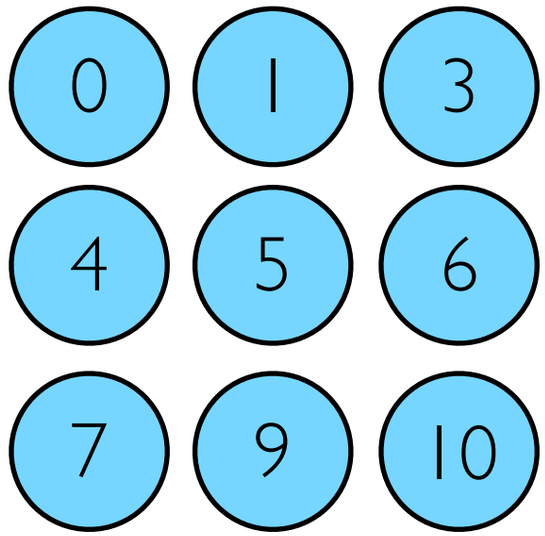

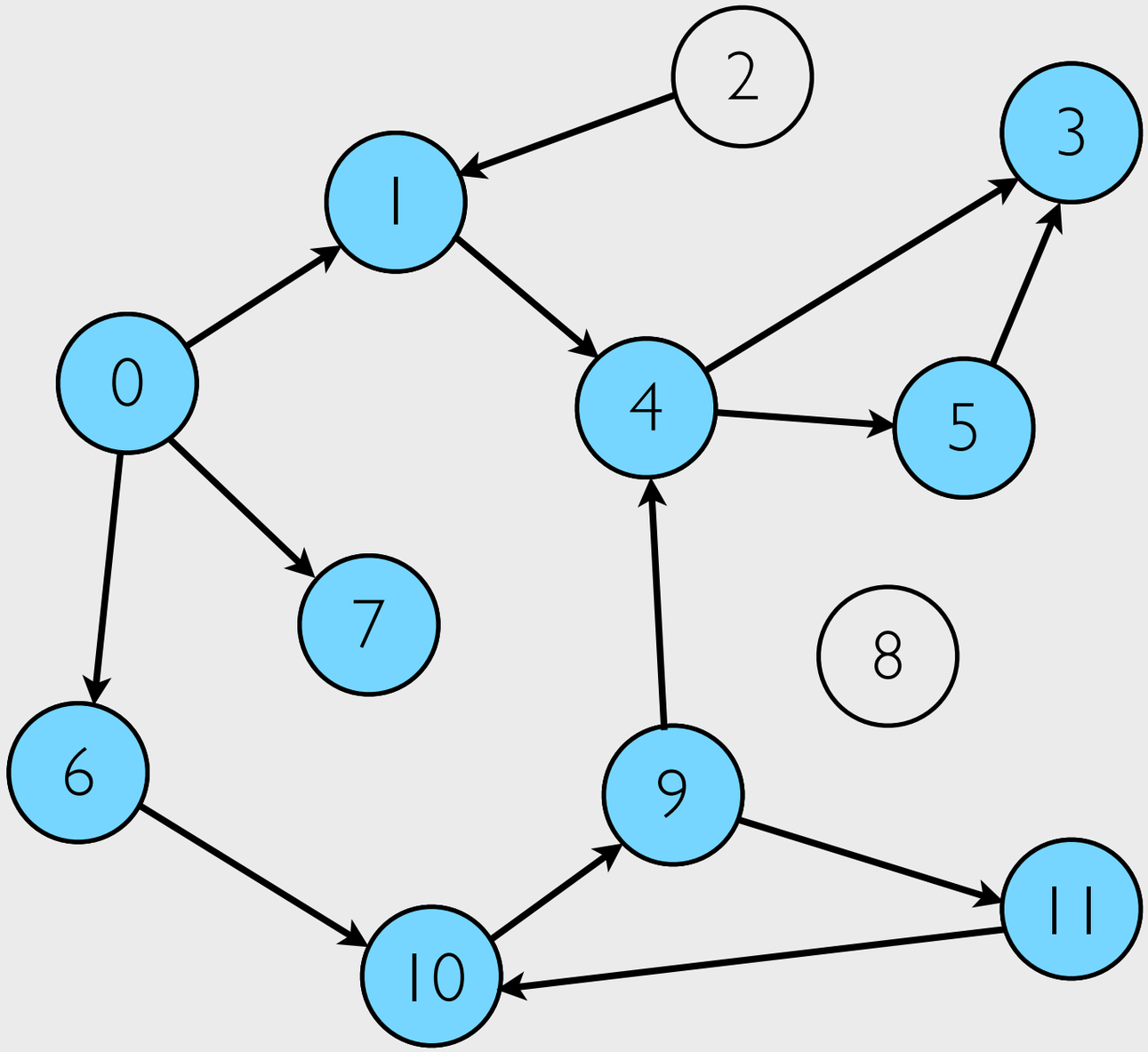

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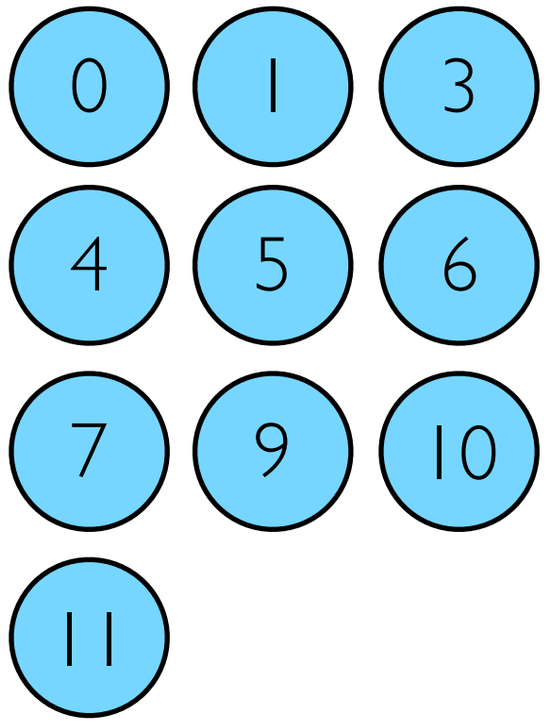

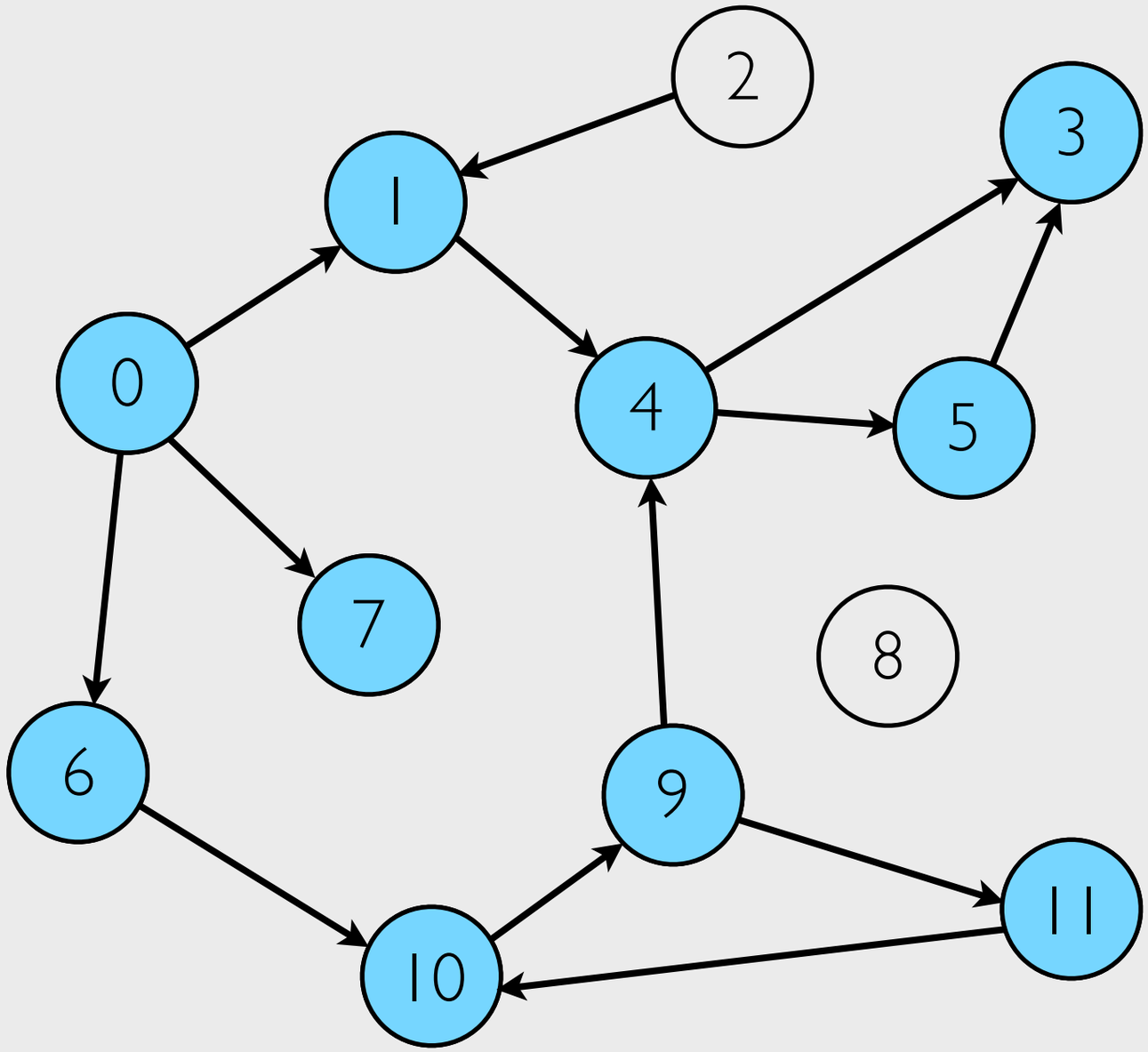

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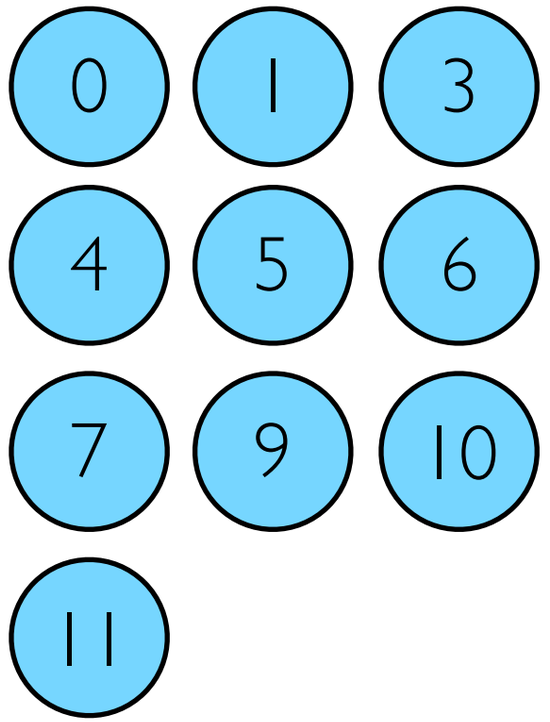

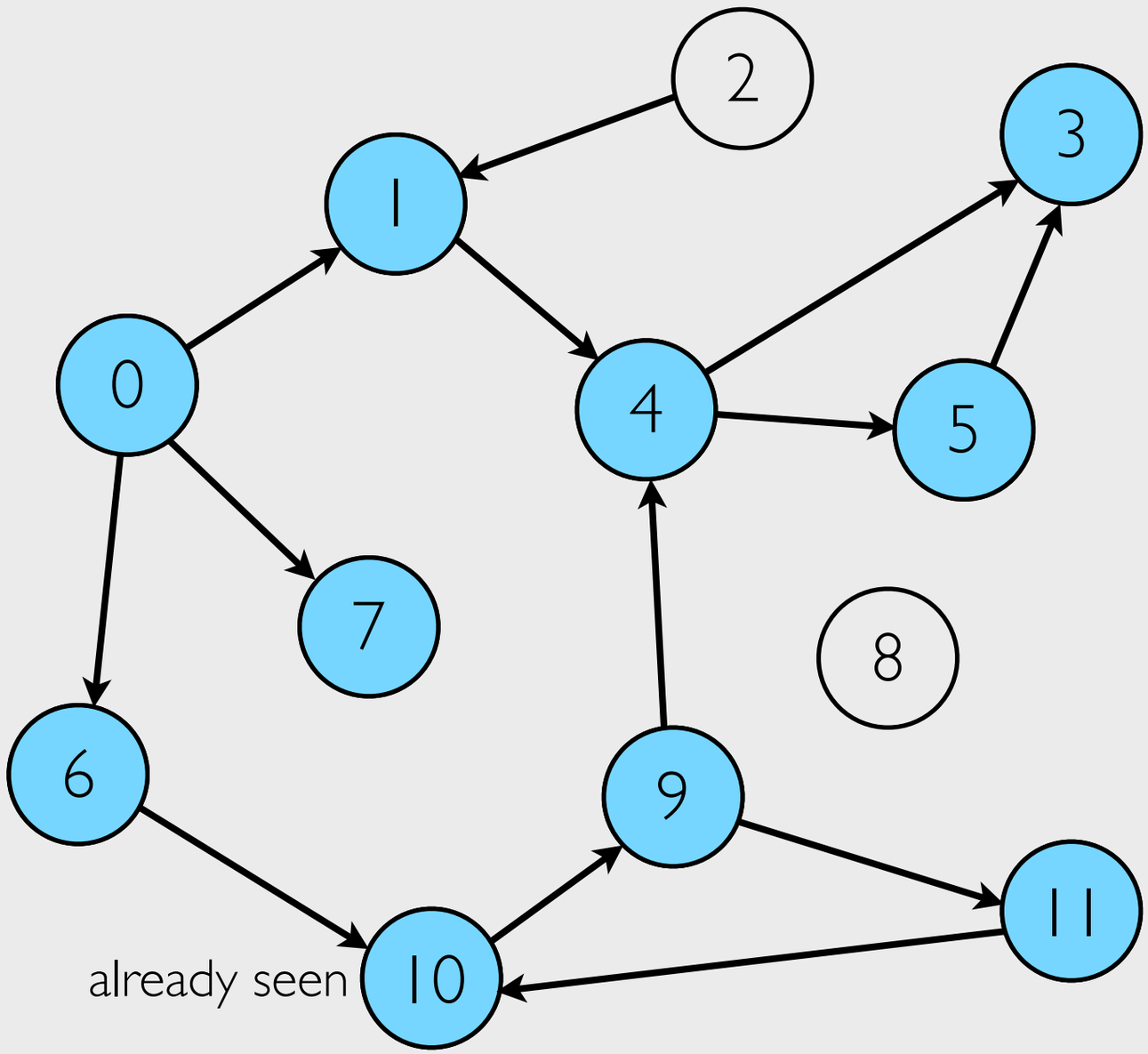

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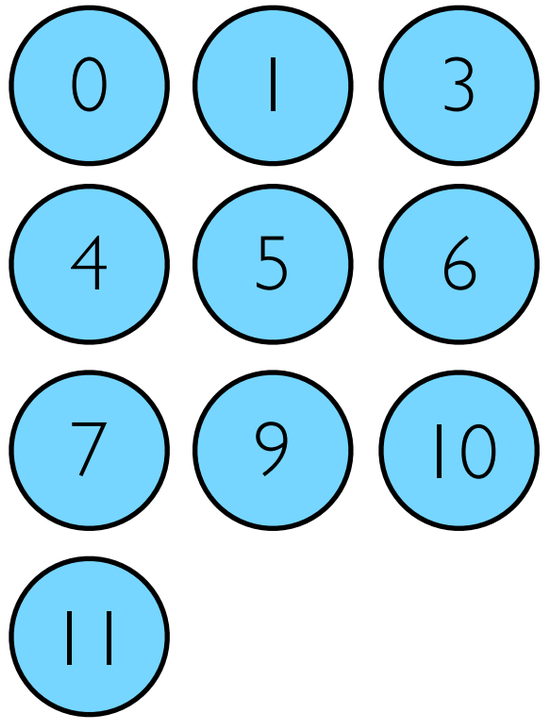

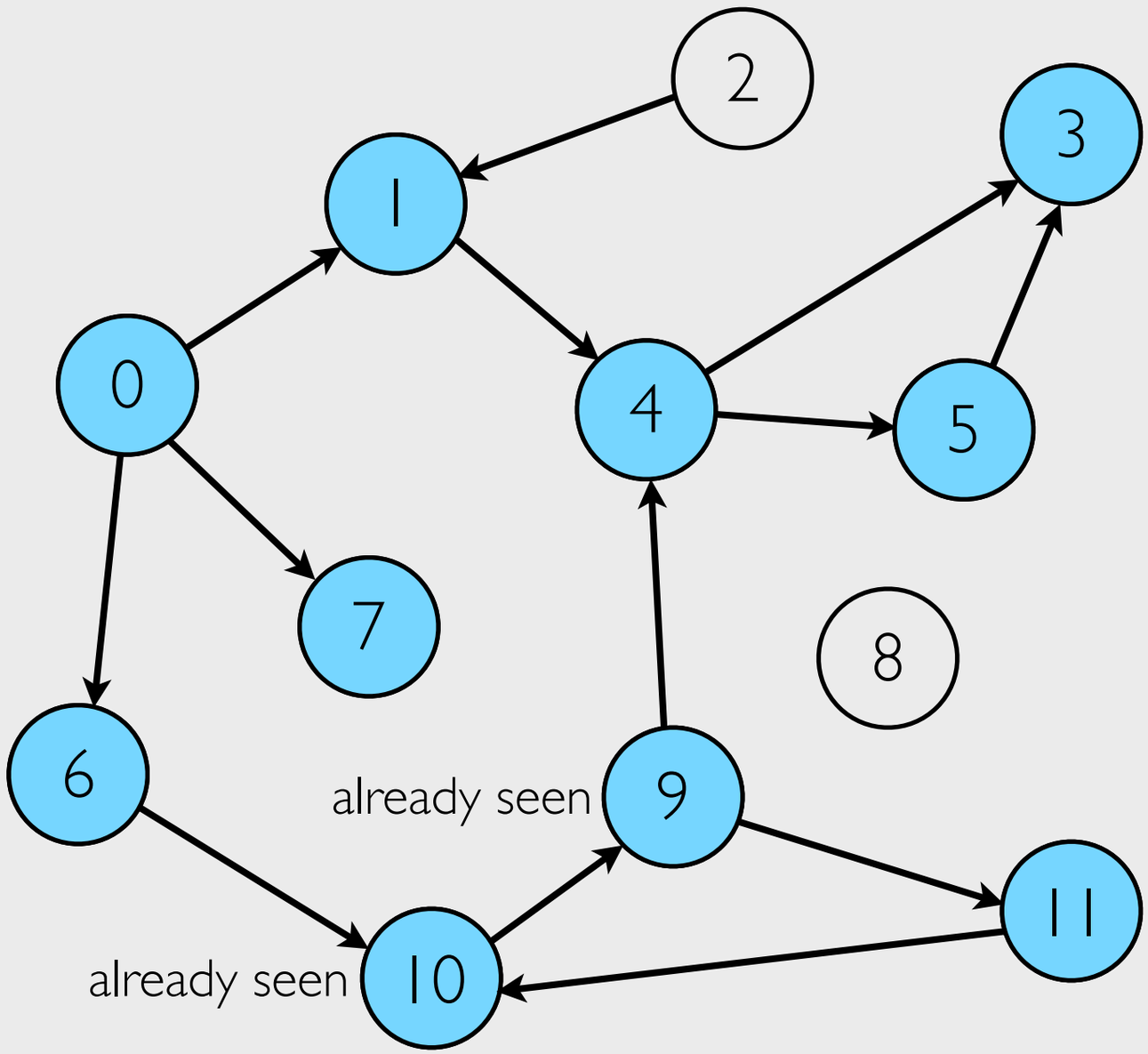

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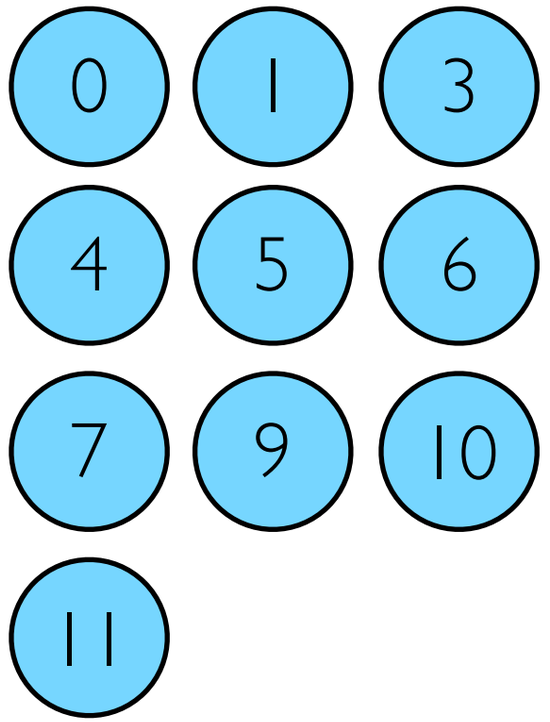

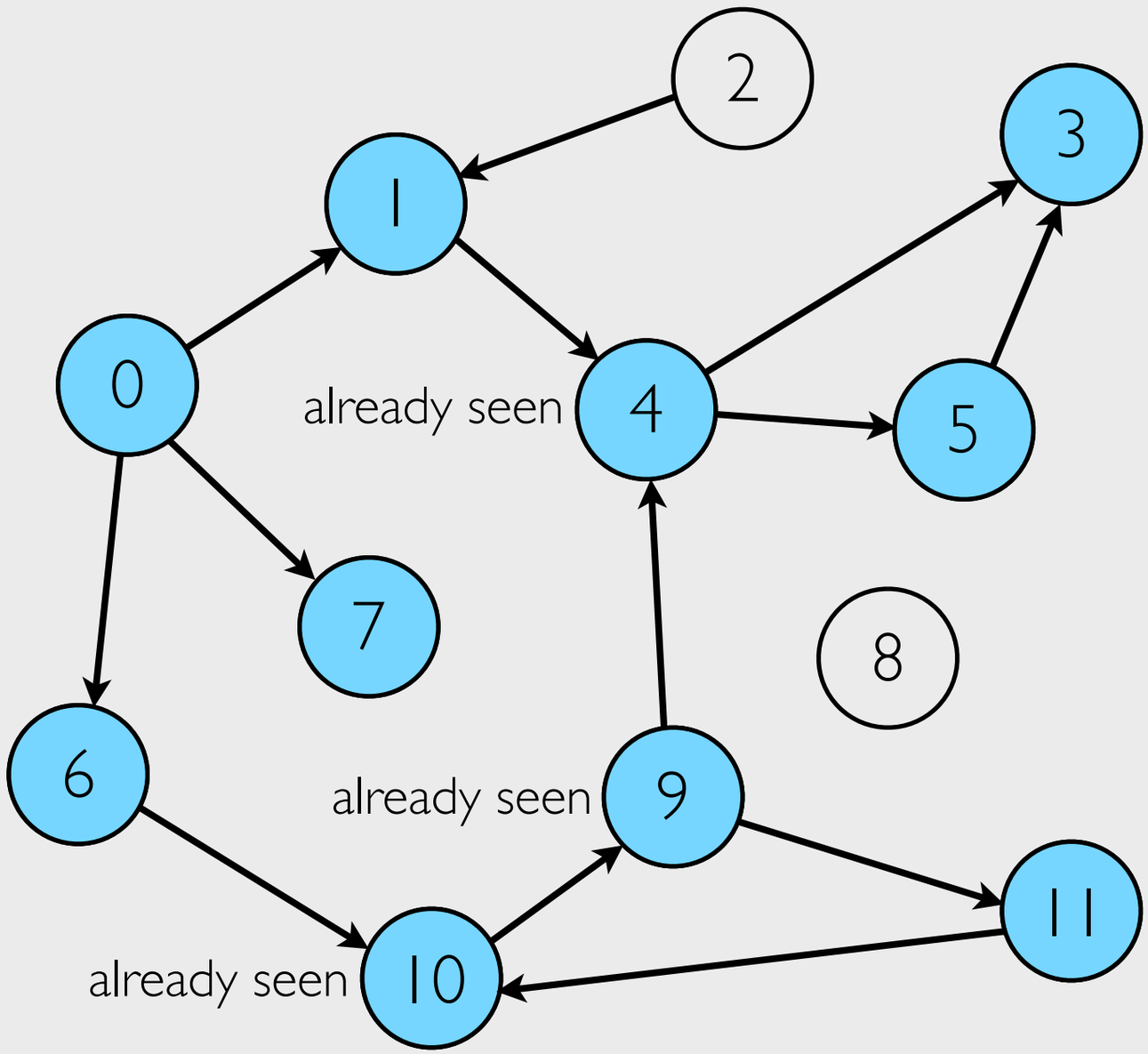
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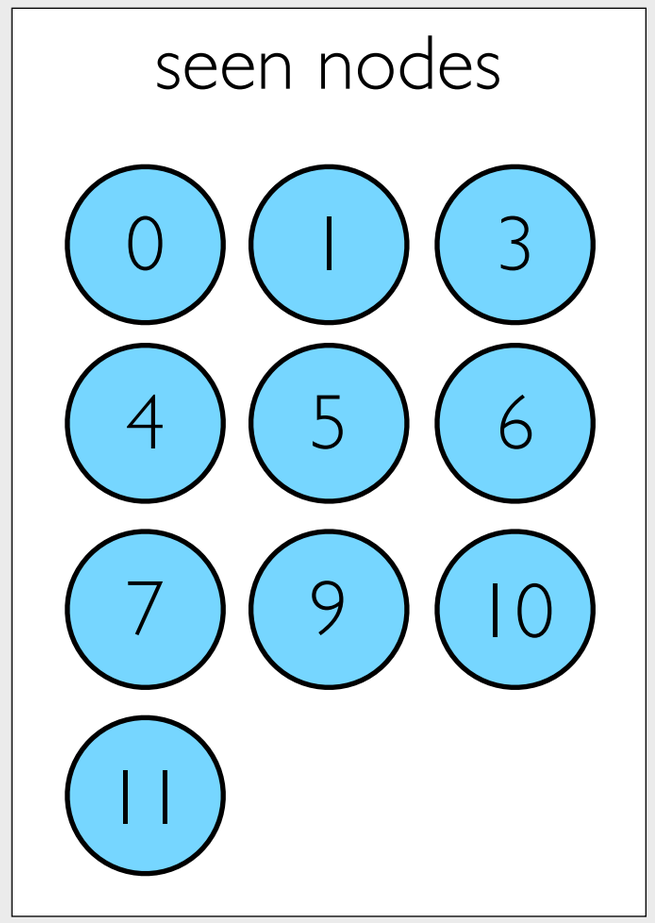
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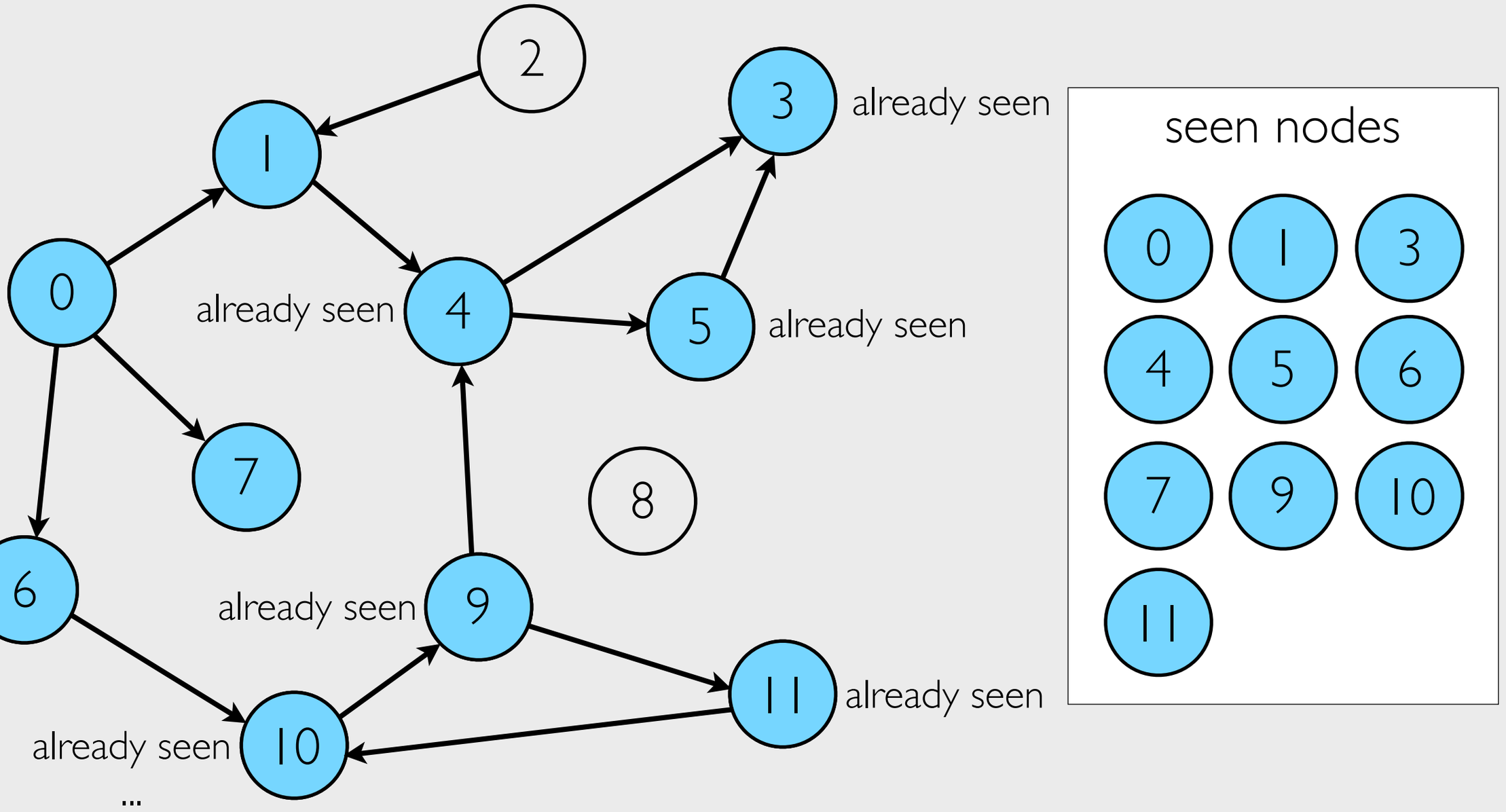
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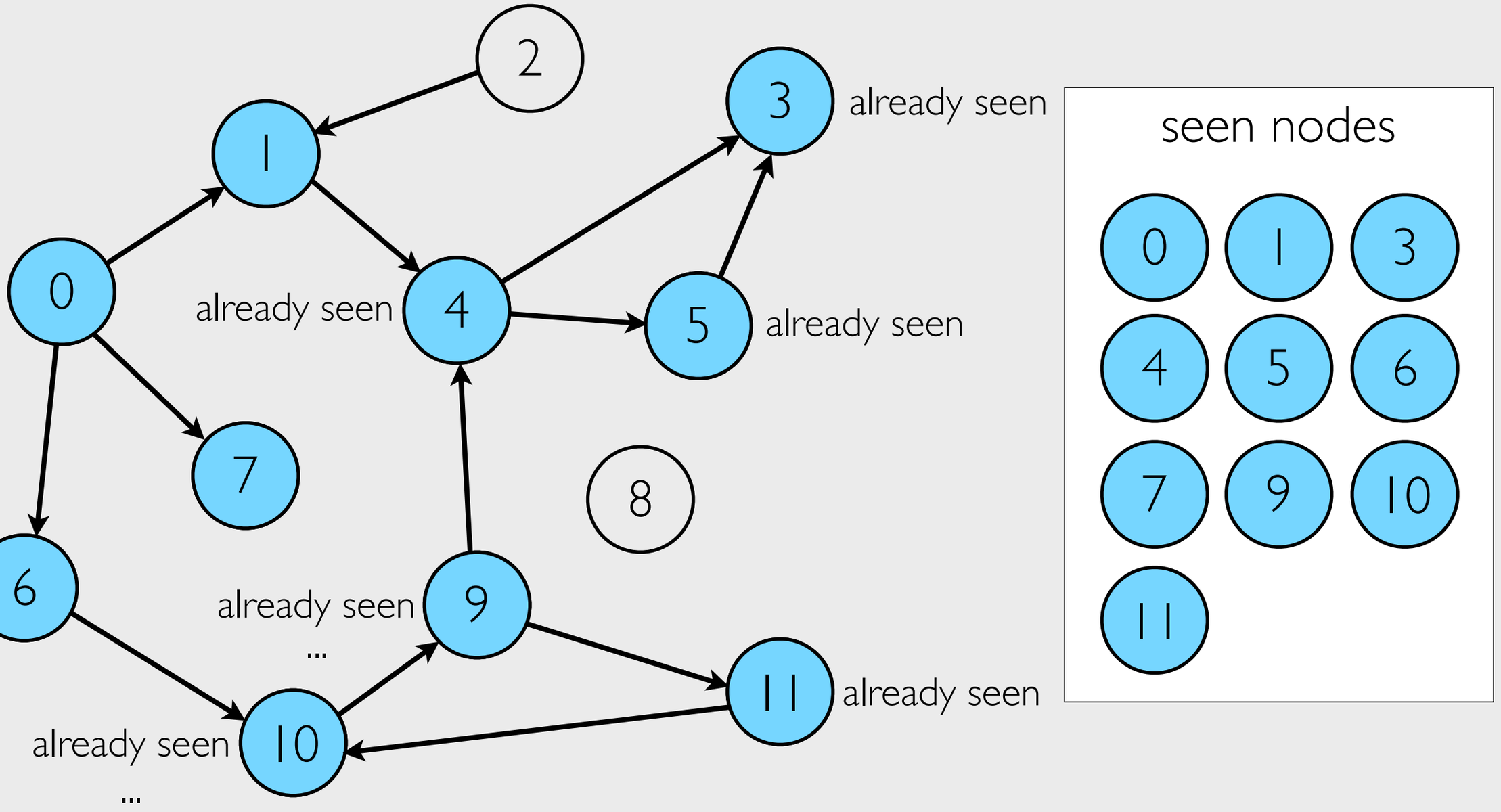
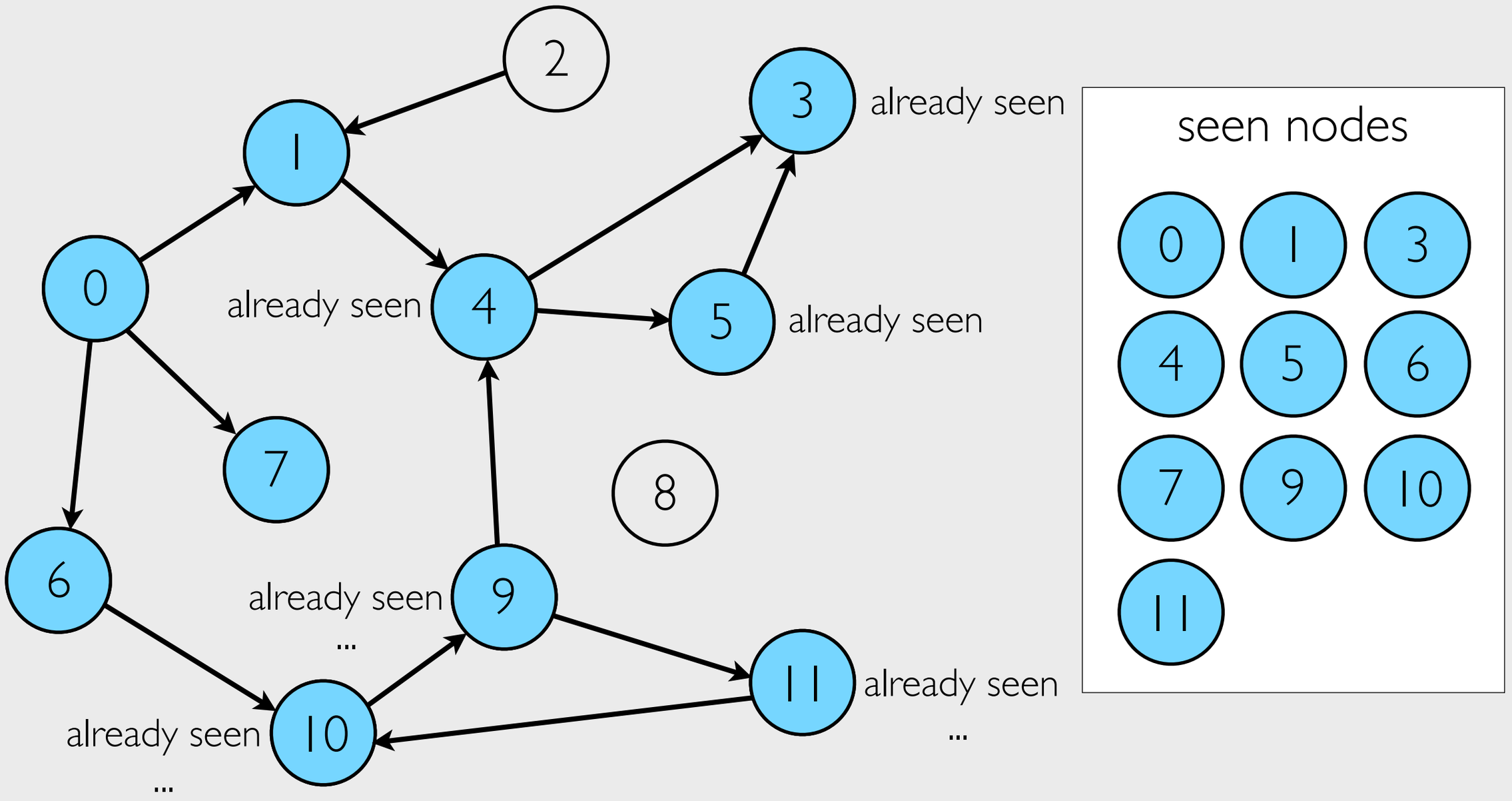
10
11


2
1
3
already seen
0
already seen
4
5
already seen
7
8
6
already seen
...
9
11
already seen
already seen
...
10
seen nodes
0
1
3
4
5
6
7
9
10
11


2
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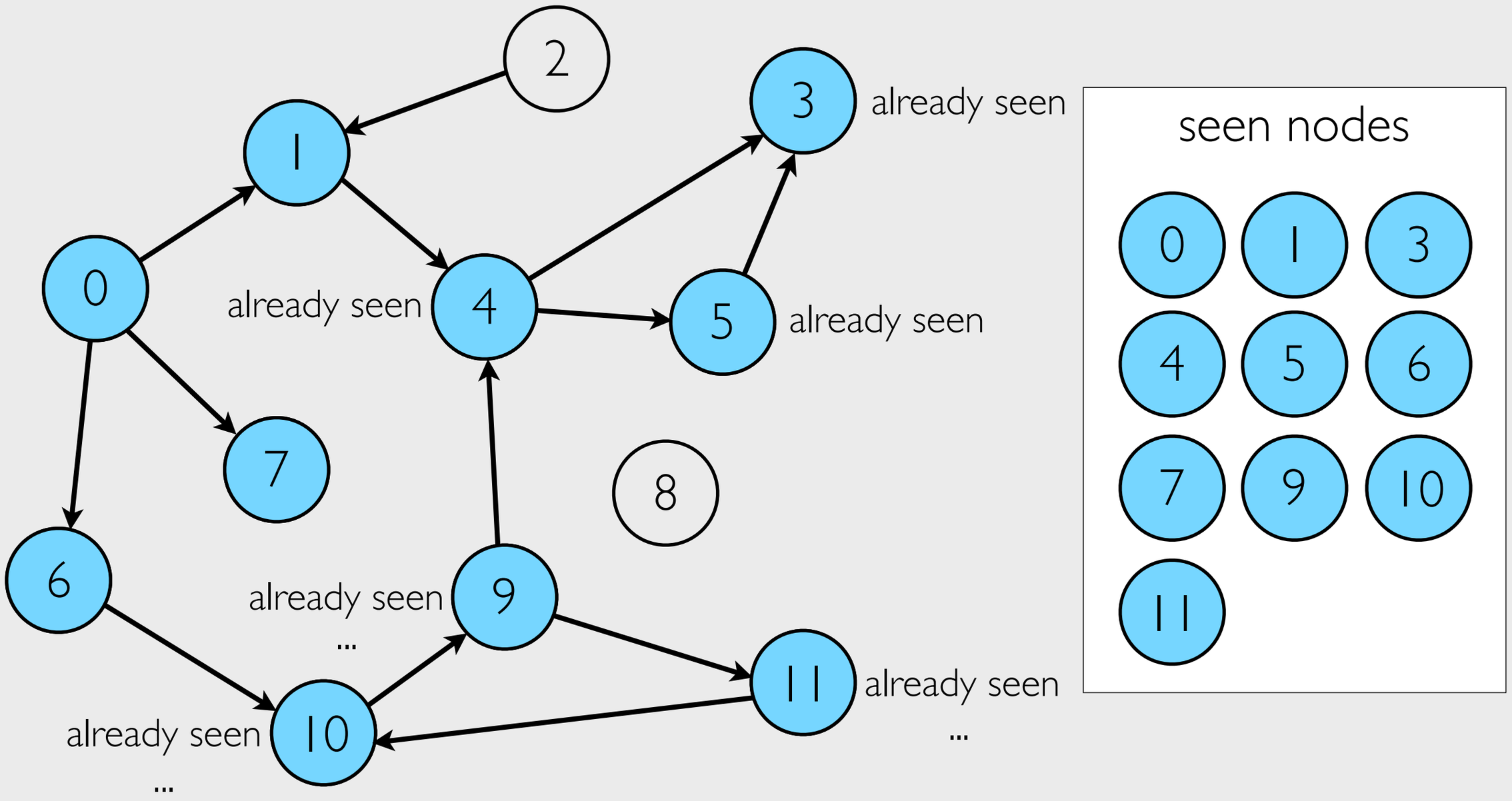
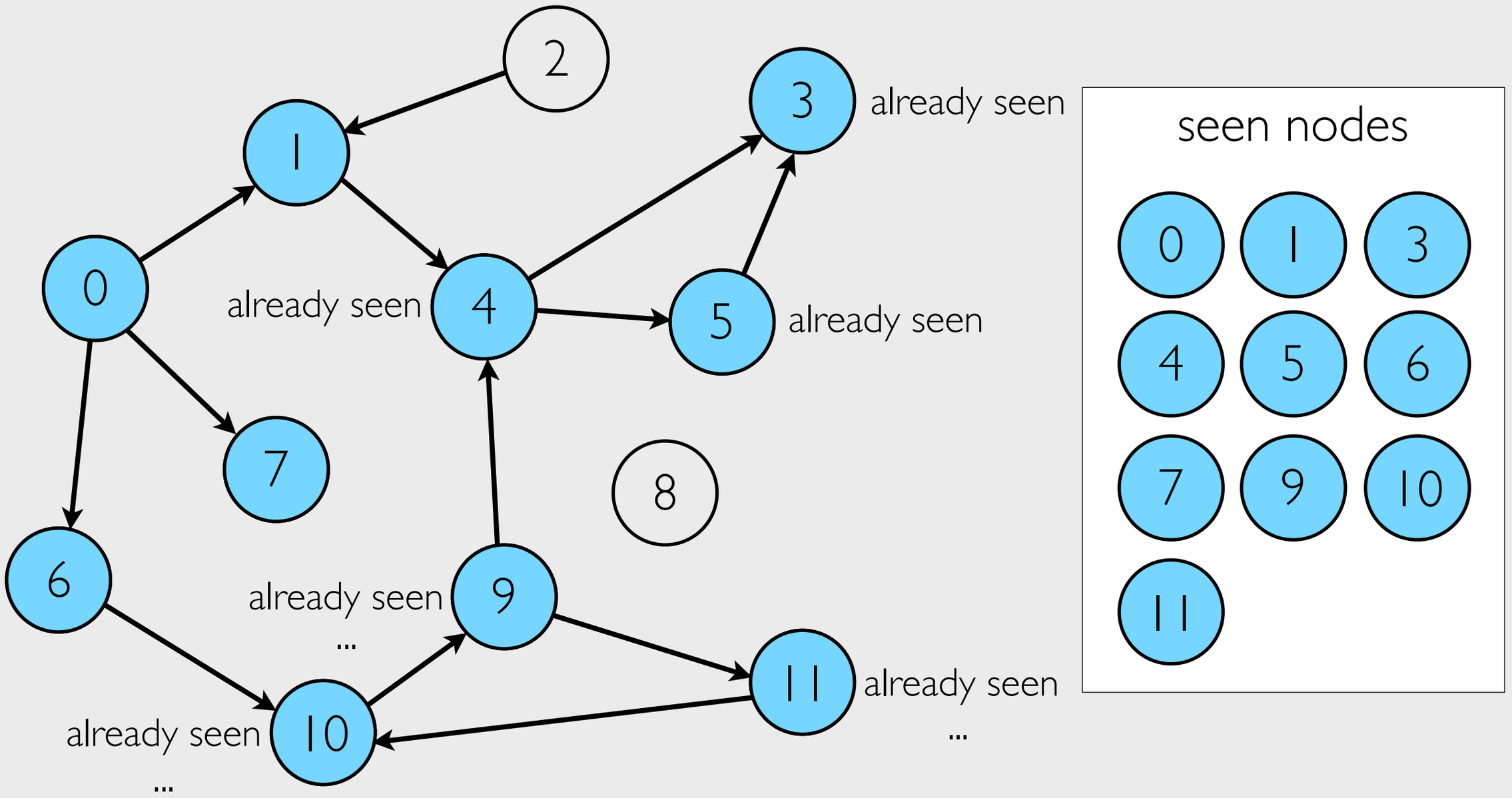
Events are updates that change an LVar's state



Events are updates that change an LVar's state

Event handlers listen for events and launch callbacks in response



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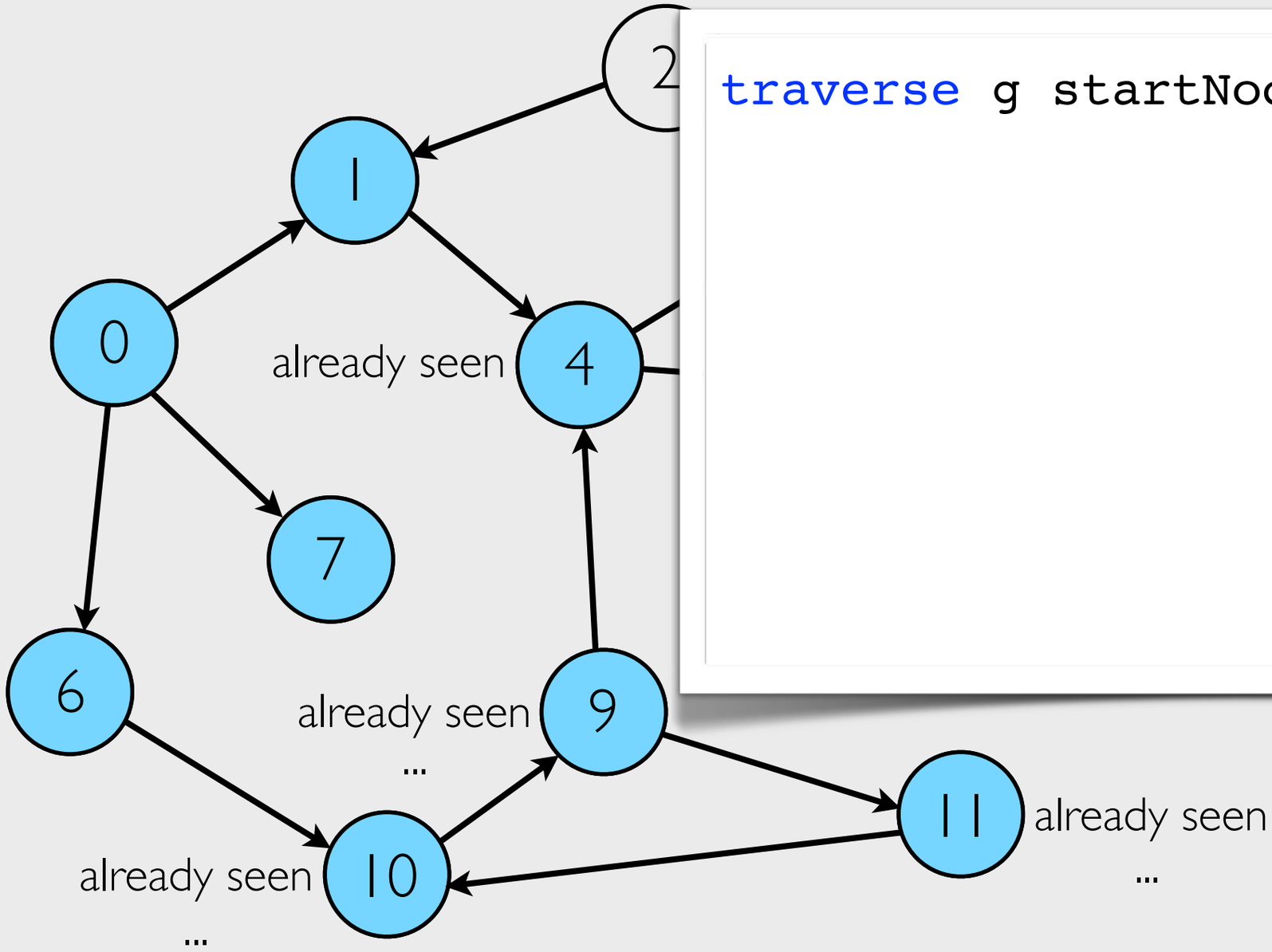


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traverse g startNode = do
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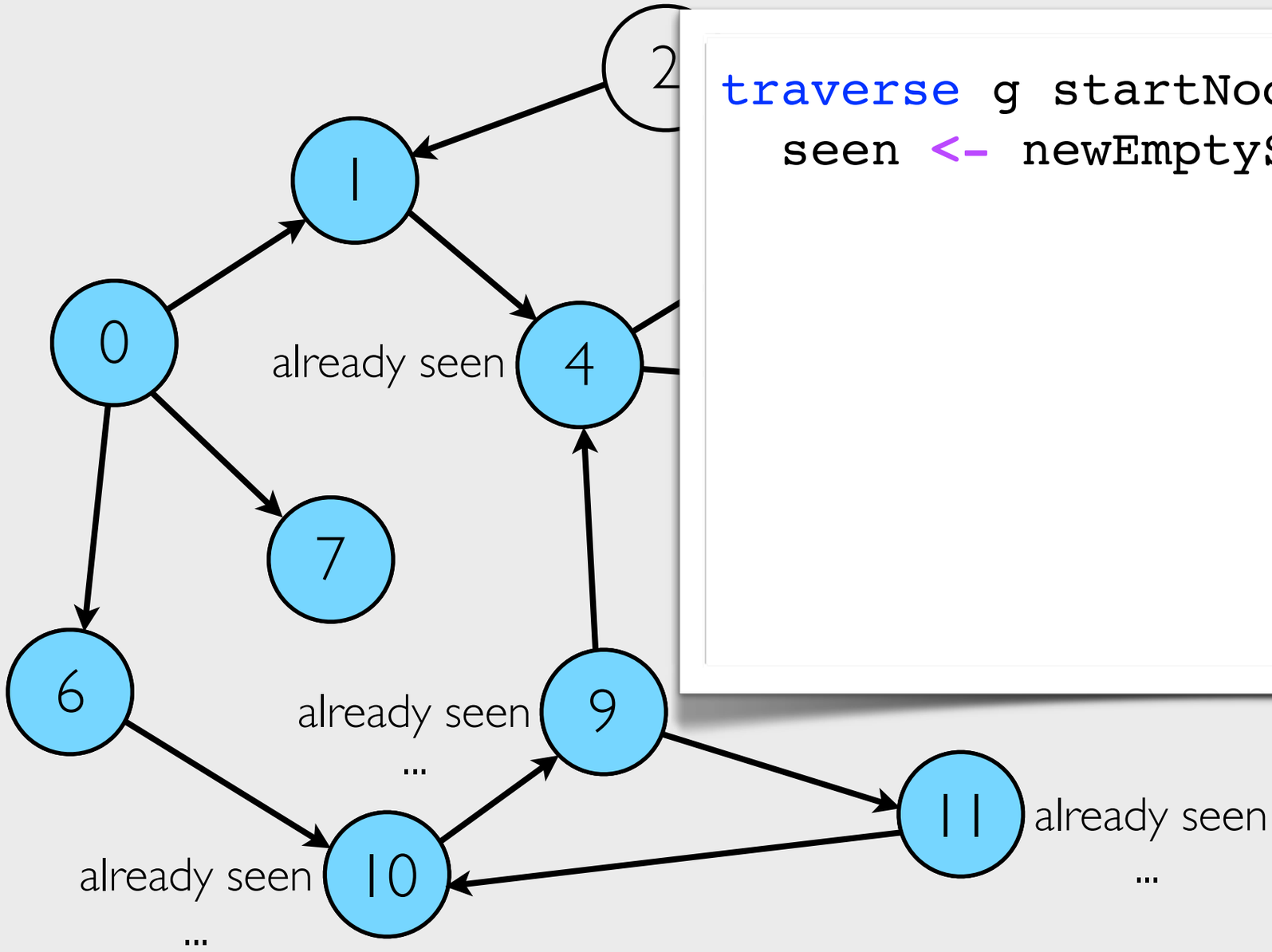


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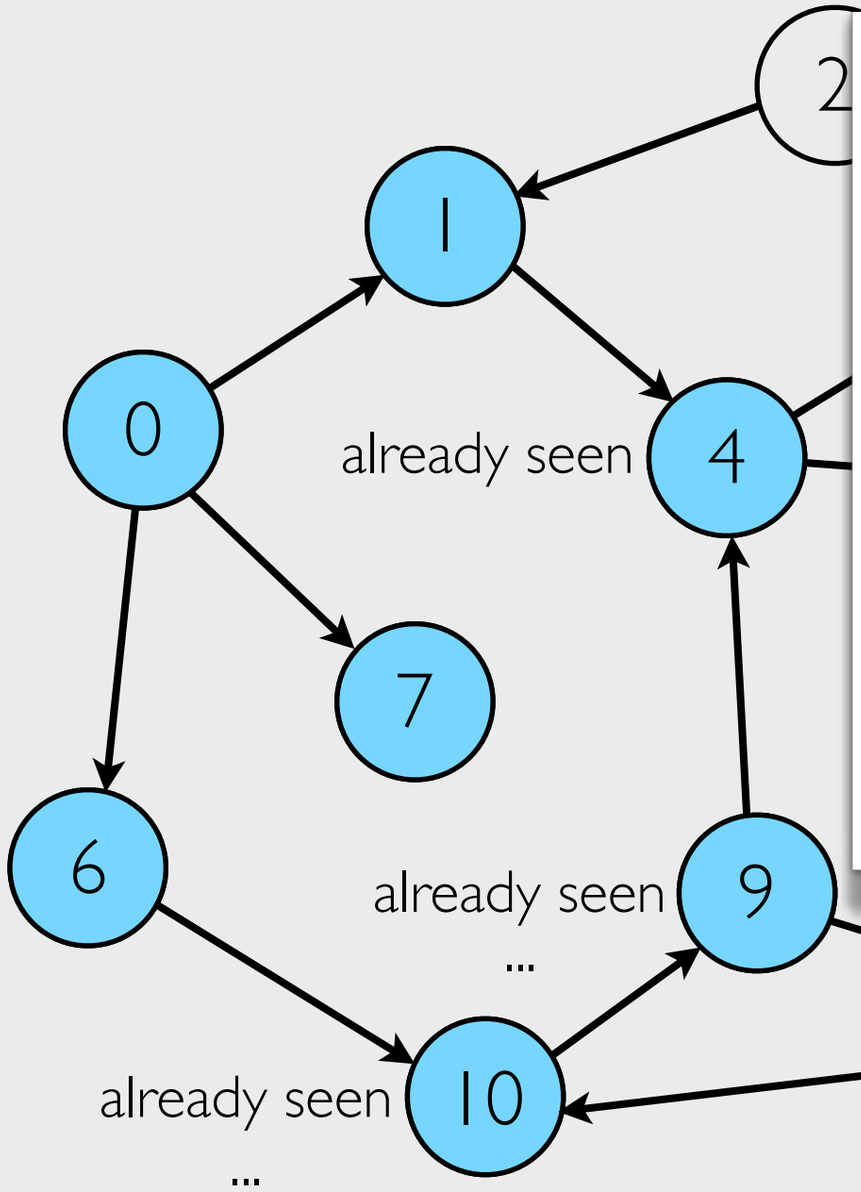


```
traverse g startNode = do
  seen <- newEmptySet
  h <- newHandler seen
       (\node -> do
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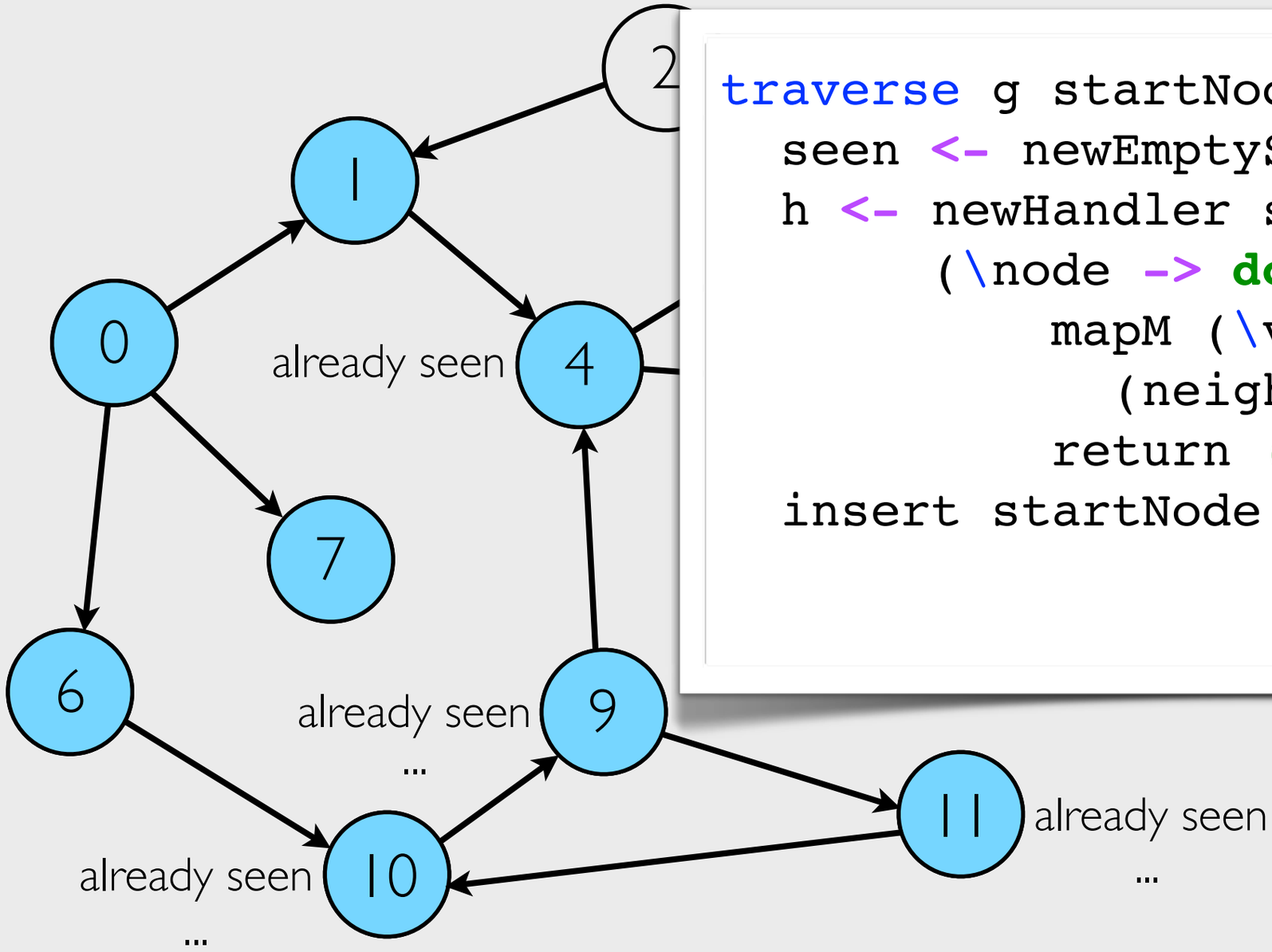


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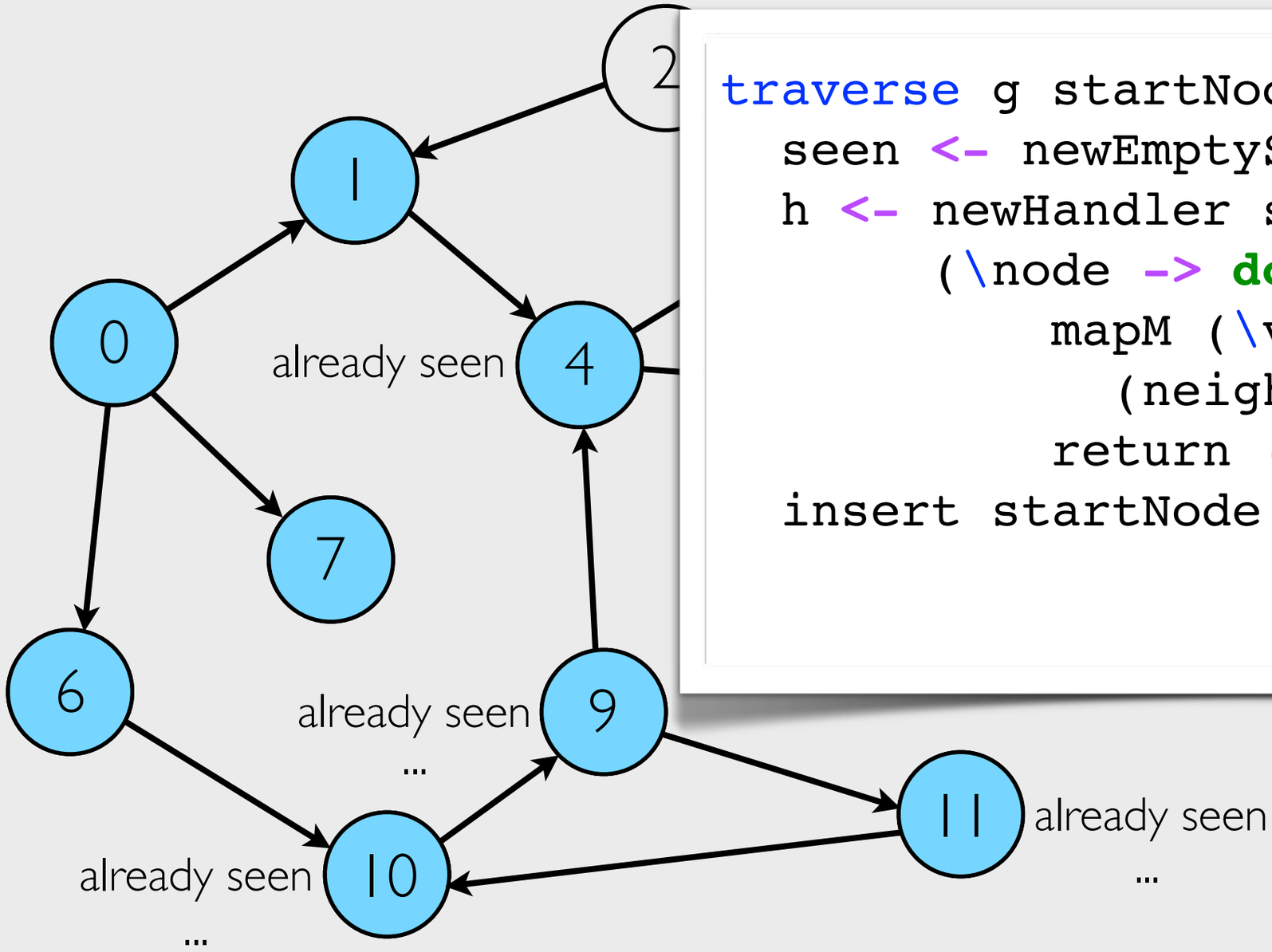
`quiesce` blocks until all callbacks launched by a given handler are done running

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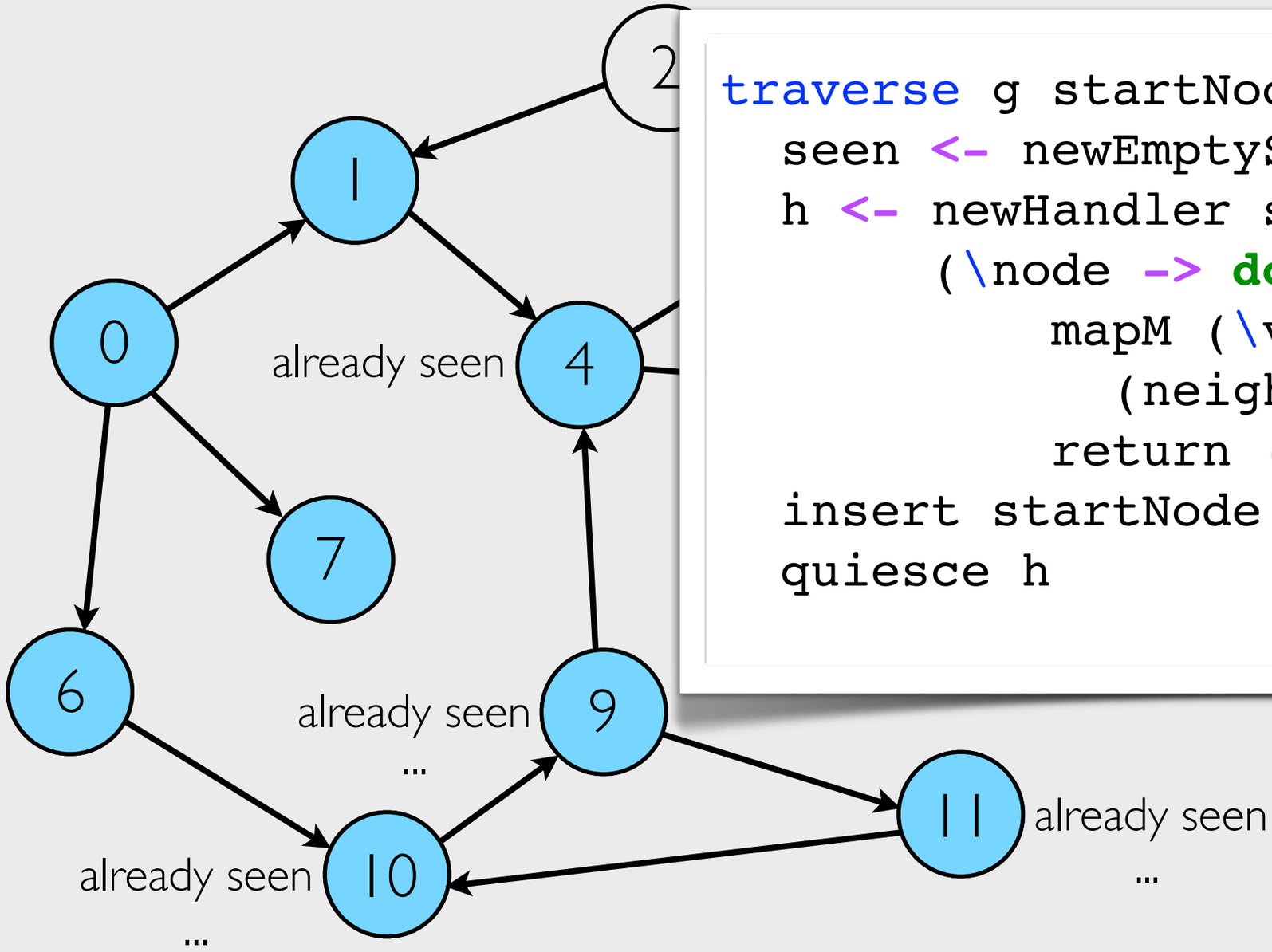


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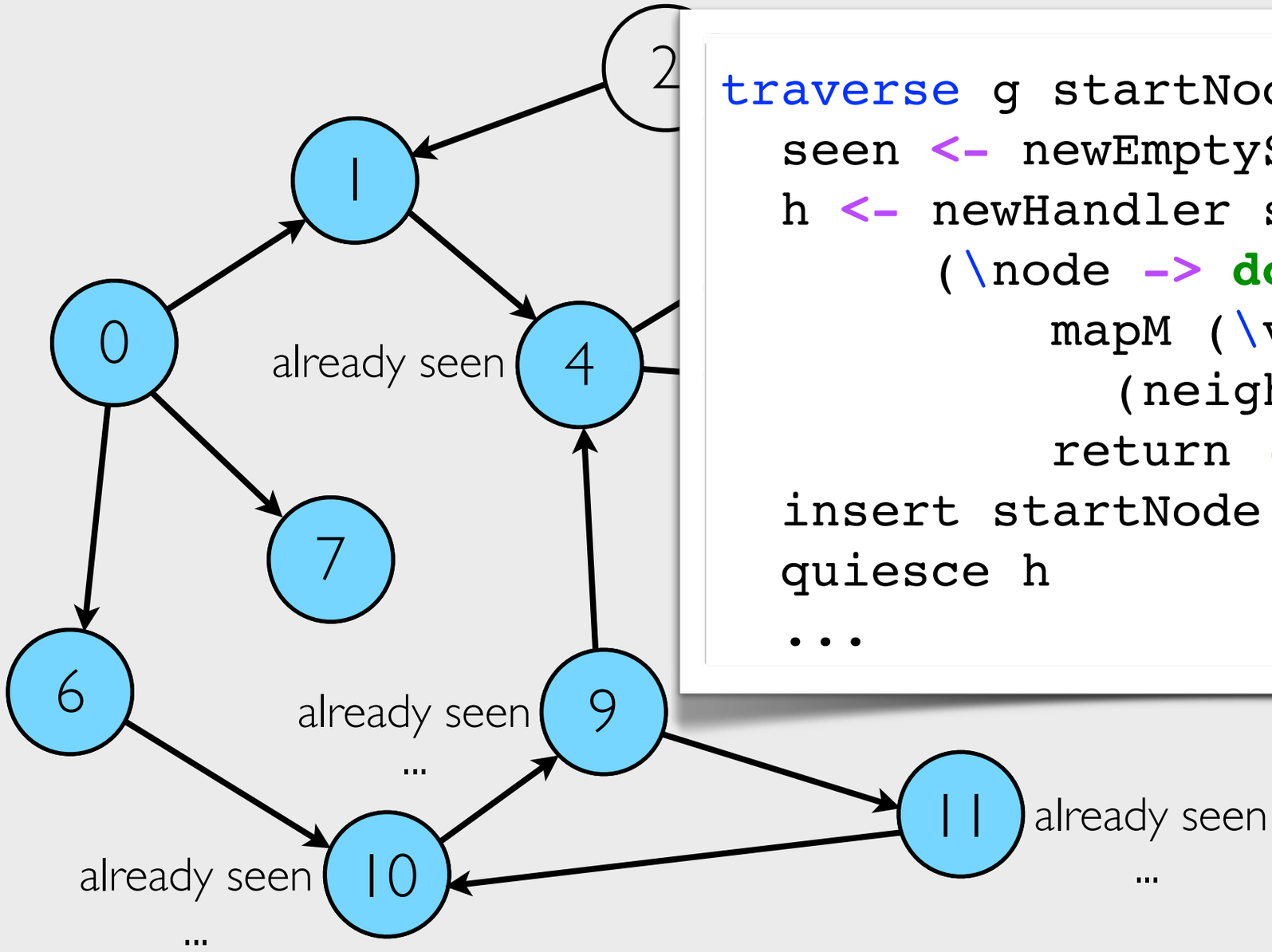


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`freeze`: exact non-blocking read

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Attempts to write to a frozen LVar raise a write-after-**`freeze`** exception

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Two possible outcomes: either the same final value or an exception

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Theorem 1 (Quasi-Determinism). *If* $\sigma \longmapsto^* \sigma'$ *and* $\sigma \longmapsto^* \sigma''$, *and neither* σ' *nor* σ'' *can take a step, then either:*

1. $\sigma' = \sigma''$ *up to a permutation on locations* π, *or*
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[(Book,1),(Shoes,1)]

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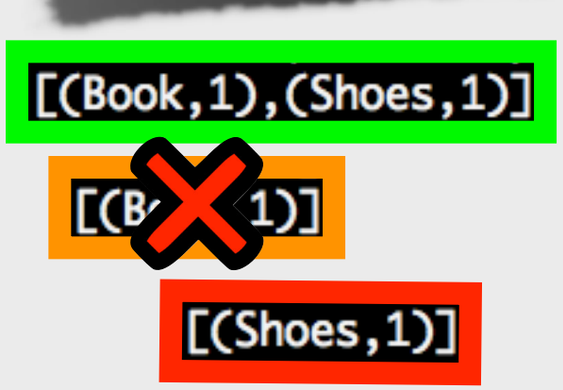

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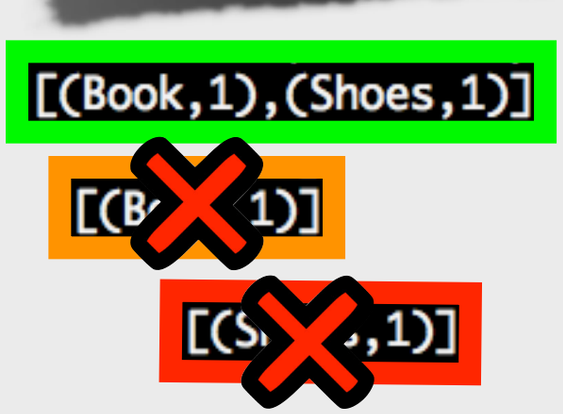

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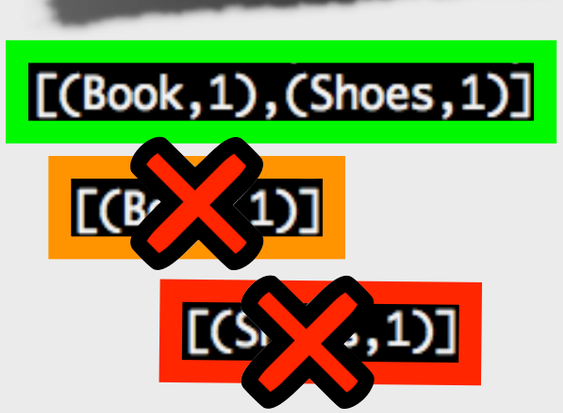

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LVish

a Haskell library for programming with LVars

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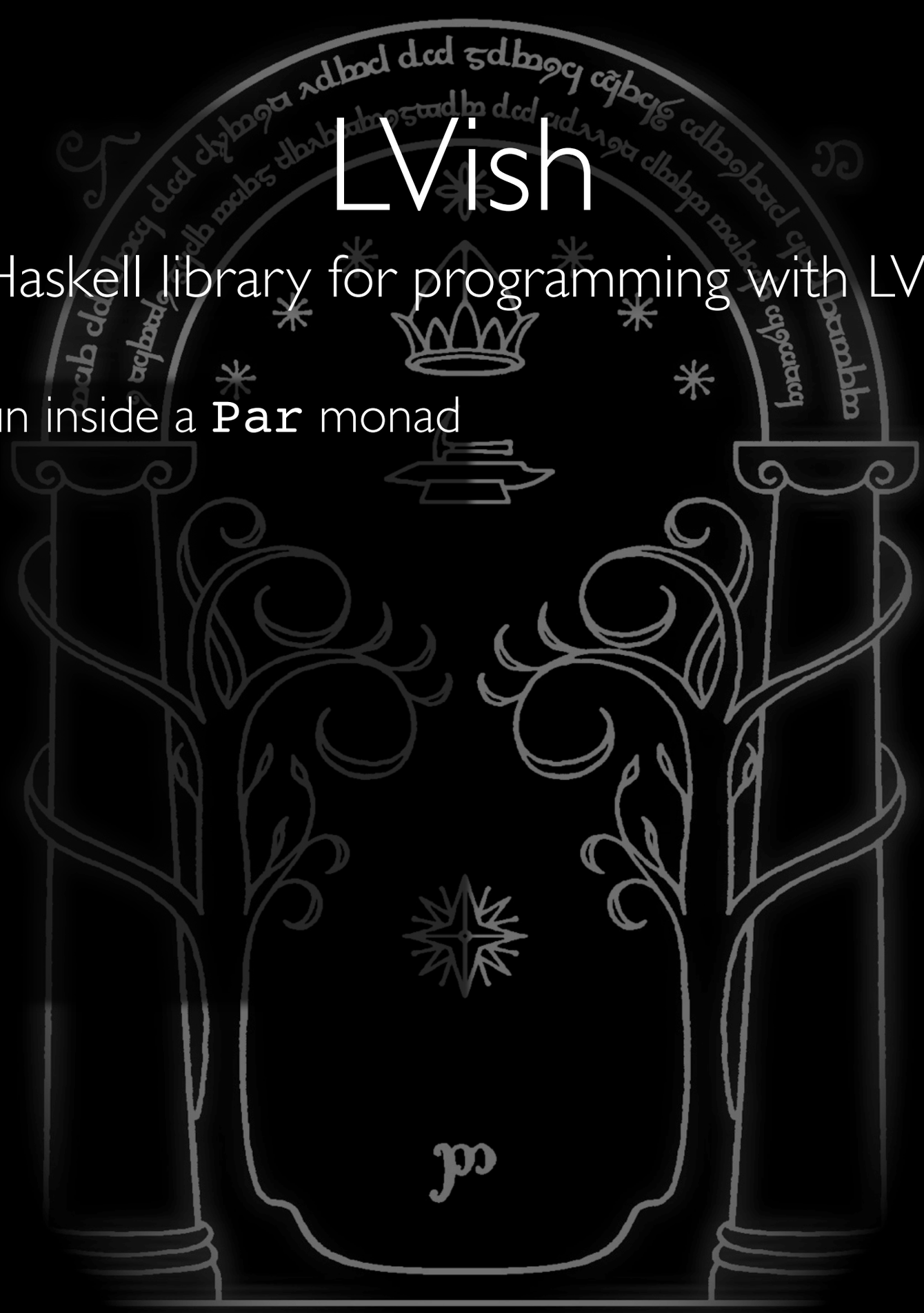
LVar operations run inside a **`Par`** monad



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Library-level threads

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Library-level threads

`Par` computations indexed by *effect level*

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`cabal install lvish` today!

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More in the paper and TR

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The LVish calculus and its quasi-determinism proof

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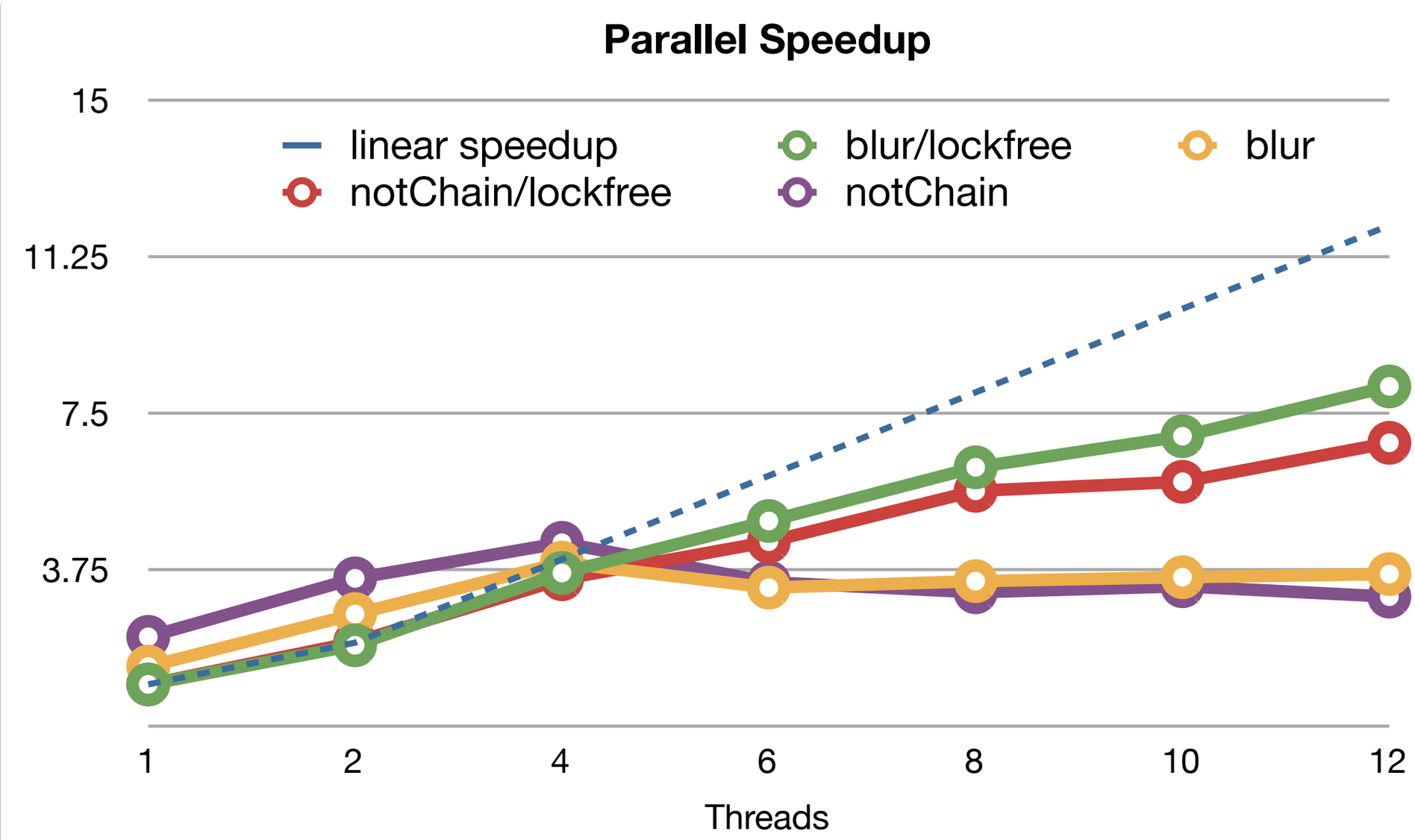

Thank you!

Email: lkuper@cs.indiana.edu
Project repo: github.com/iu-parfunc/lvars
Code from this talk: github.com/lkuper/lvar-examples
More LVars papers: cs.indiana.edu/~lkuper
Research blog: composition.al