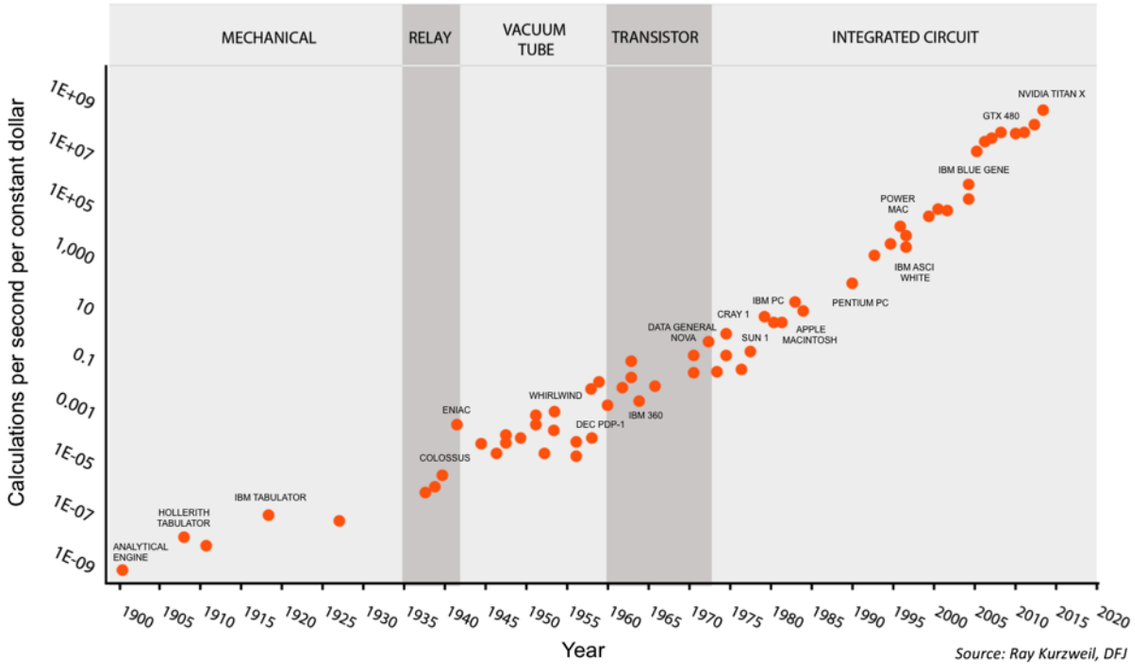
# Transactional Futures

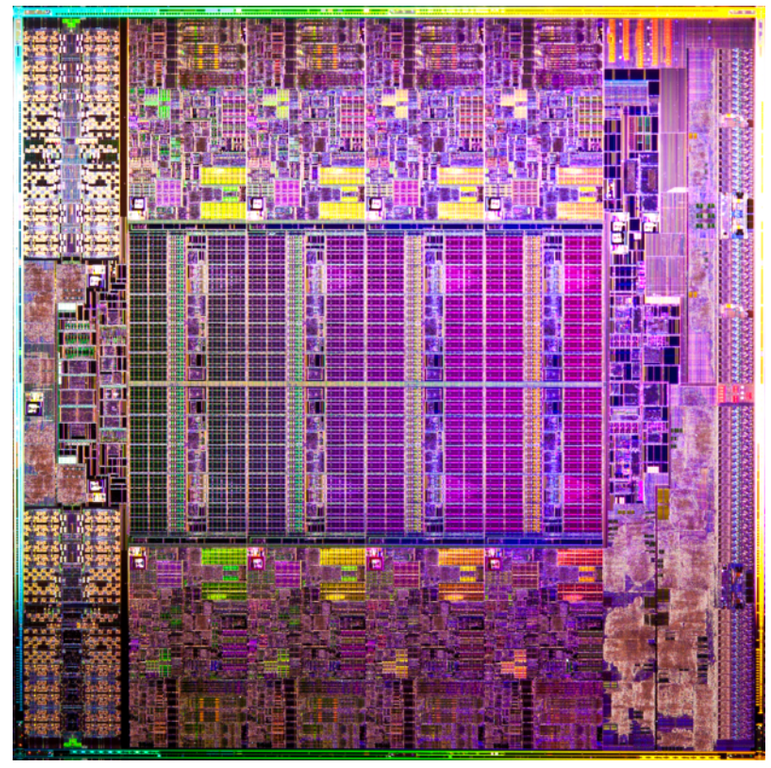
## Parallelism in Software Transactions

Janwillem Swalens


# Context: concurrency

Moore's law



Concurrency is **useful** but **difficult**

Concurrency models provide **safety guarantees**

# Three concurrency models

- **Futures:** deterministic
- **Transactions:** non-deterministic, shared memory
- **Actors:** non-deterministic, message passing

**Separately** they work **fine**,
but **combining** them leads to **problems**.

# Three concurrency models

- **Futures**: deterministic
- **Transactions**: non-deterministic, shared memory
- **Actors**: non-deterministic, message passing

**Separately** they work **fine**,
but **combining** them leads to **problems**.

# Futures for parallelism

(**`fork`** `e`) returns `f`

(**`join`** `f`) returns result of `e`

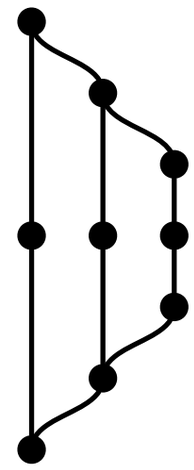
```
(defn fib [n]
  (if (< n 2)
    n
    (let [a (fib (- n 1))
          b (fib (- n 2))]
      (+ a b))))
```

# Futures for parallelism

(**fork** e) returns f

(**join** f) returns result of e

```
(defn fib [n]
  (if (< n 2)
    n
    (let [a (fork (fib (- n 1)))
          b (fork (fib (- n 2)))]
      (+ (join a) (join b)))))
```

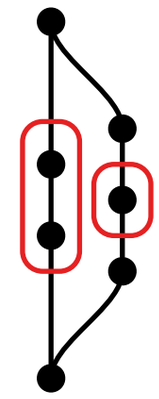


# Transactions for shared memory

```
(ref v)
(atomic e)
(deref r)
(ref-set r v)
```

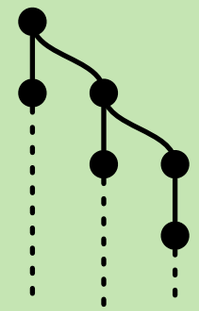
**serializability**

```
(def checking (ref 100))
(def savings  (ref 500))
(fork
  (atomic
    (ref-set checking (- (deref checking) 10))
    (ref-set savings  (+ (deref savings)  10))))
(fork
  (atomic
    (println “You own €” (+ (deref checking)
                            (deref savings)))))
```



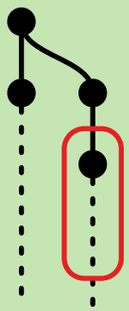
# Nesting futures & transactions

```
(fork
  (fork
    …))
```



Nested task parallelism

```
(fork
  (atomic
    …))
```

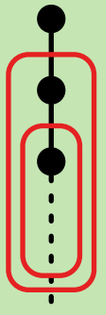


Transactions

```
(atomic
  (fork
    …))
```


In-transaction parallelism

```
(atomic
  (atomic
    …))
```

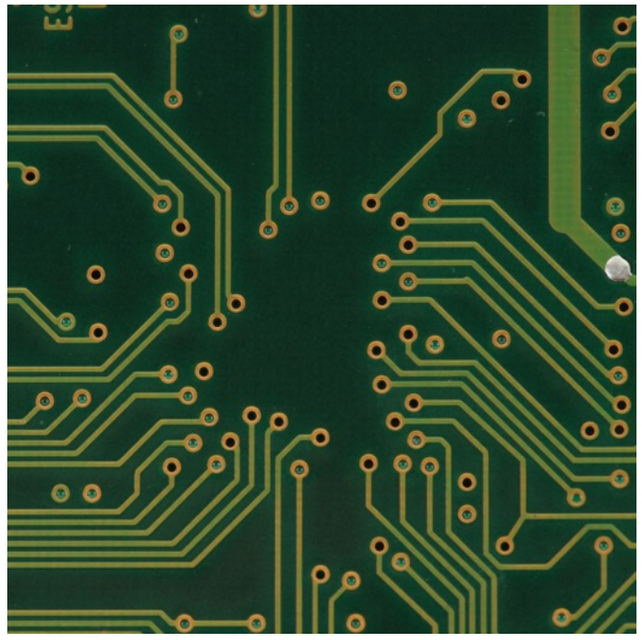


Nested transactions (open/closed)

# Example: Labyrinth

| | | | | | |
|---|---|---|---|---|---|
| ■ | ■ | | 2d | | 2s |
| ■ | 1s | | | | ■ |
| | | 4d | | | |
| | ■ | | | 1d | |
| 3s | ■ | | | | |
| | | 3d | | | 4s |

| | | | | | |
|---|---|---|---|---|---|
| ■ | ■ | | 2d | 2 | 2s |
| ■ | 1s | 1 | 1 | 1 | ■ |
| | | 4d | | 1 | |
| | ■ | 4 | | 1d | |
| 3s | ■ | 4 | 4 | 4 | 4 |
| 3 | 3 | 3d | | | 4s |



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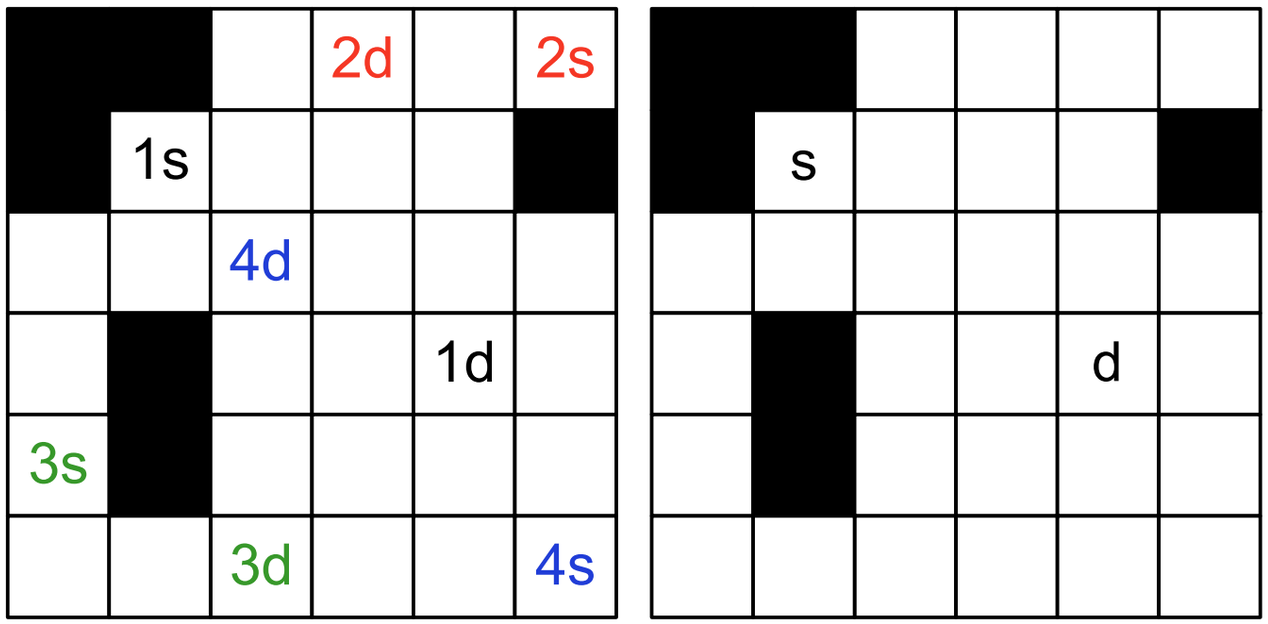



```
(for [[src dst] input-pairs]
  (let [local-grid (copy grid)]
    (expand src dst local-grid)
    (add-path grid
      (traceback local-grid dst))))
```

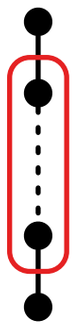
```
(defn expand [src dst
  (loop [q
    (if (empty? q
      false

      true

      (rest q
      (expand-point (first q)
```

breadth-first search

```
(defn expand-point [pt grid]
  (atomic
    (let [neighbors …]
      (for [n neighbors]
        (ref-set n …))
      neighbors)))
```



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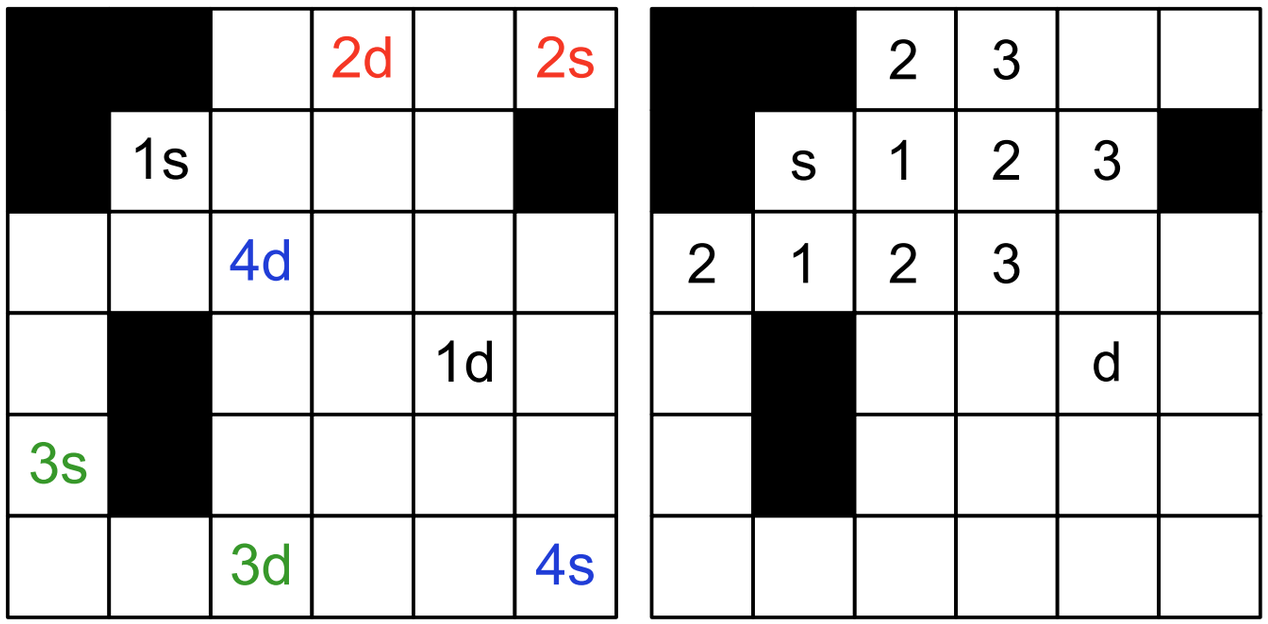


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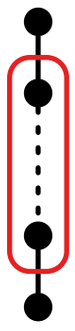

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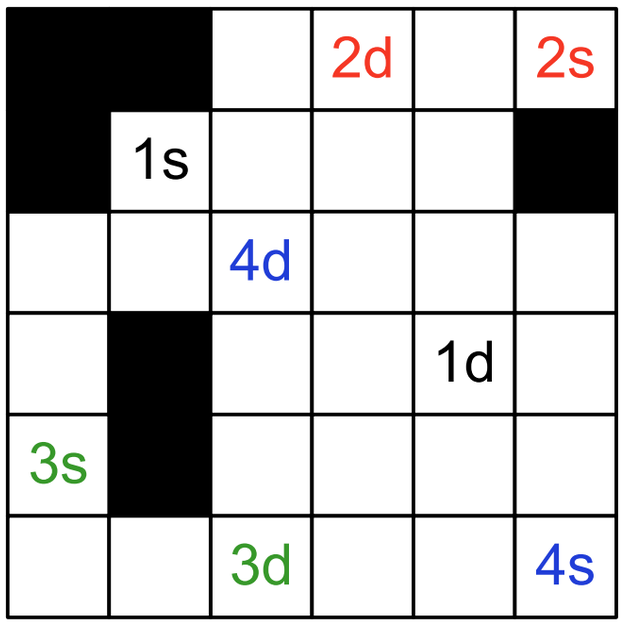


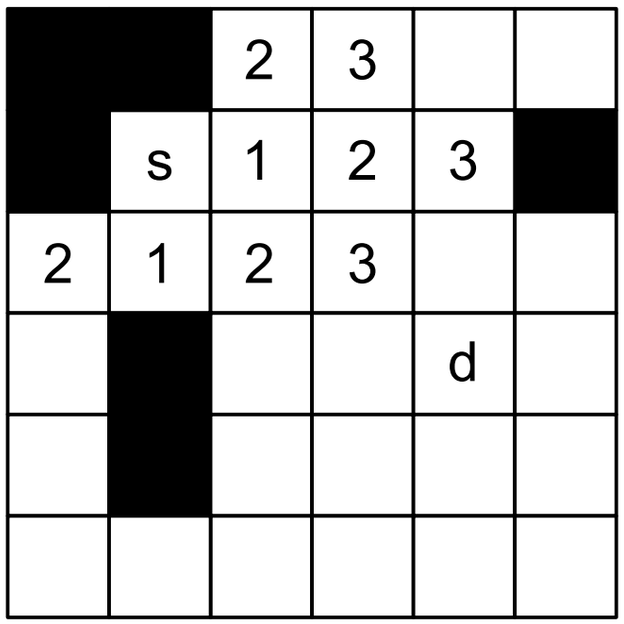


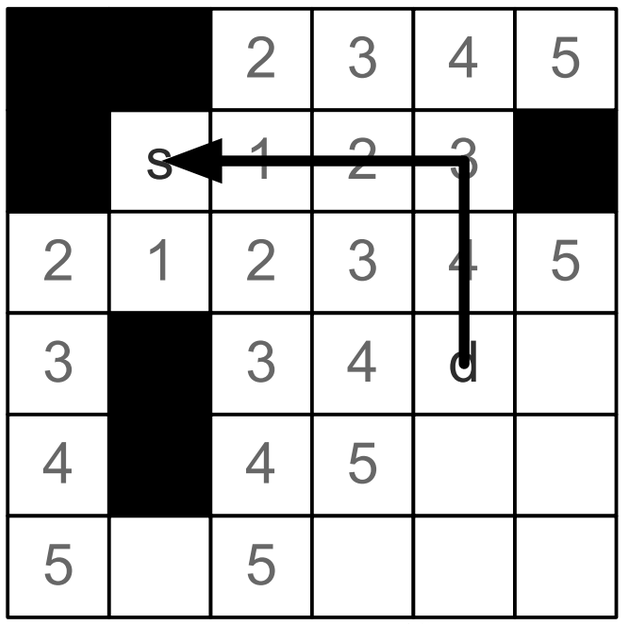


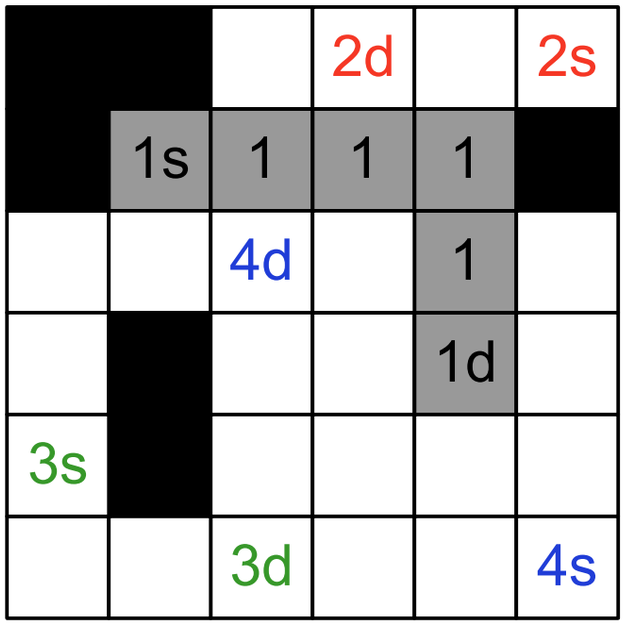


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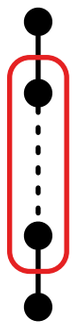
**breadth-first search**



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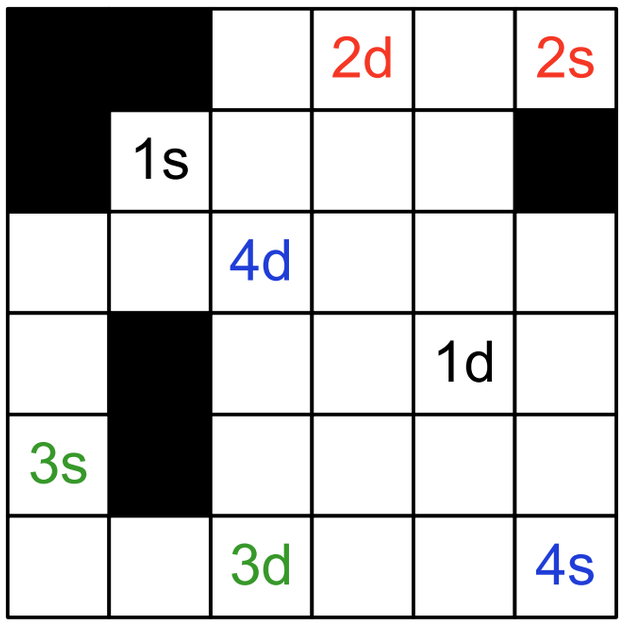


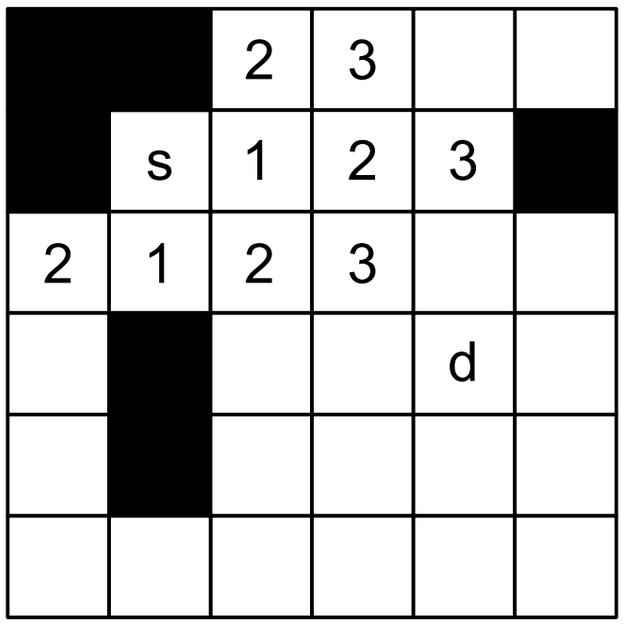


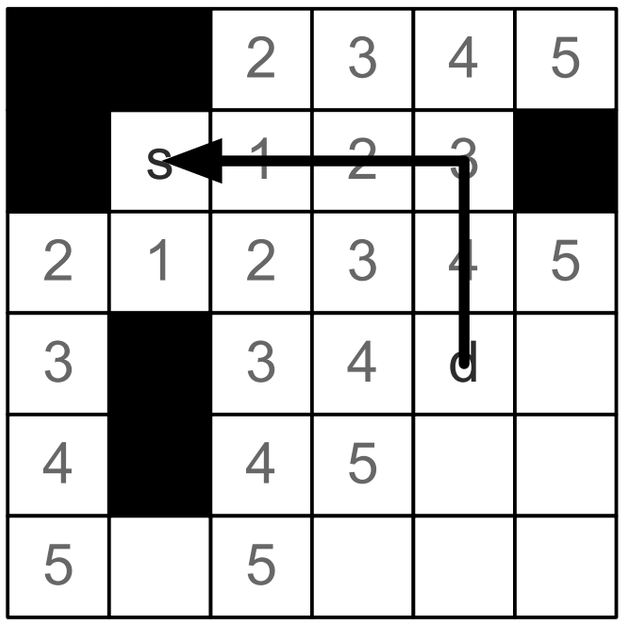


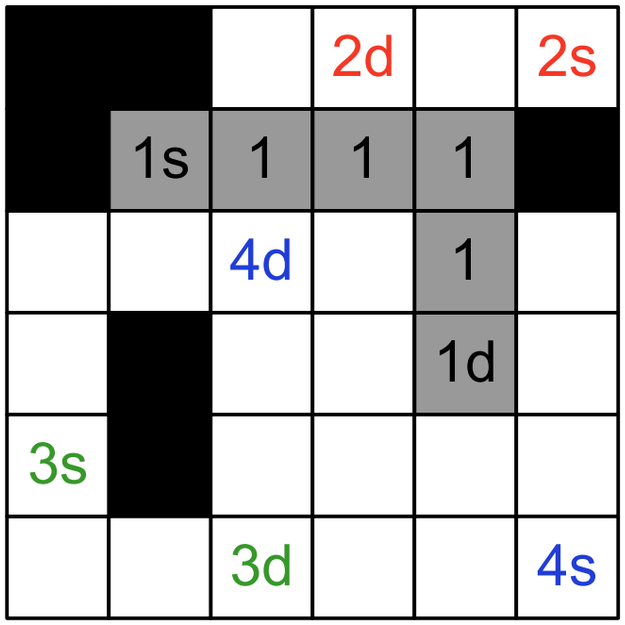


```
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  (fork [local-grid (copy grid)]
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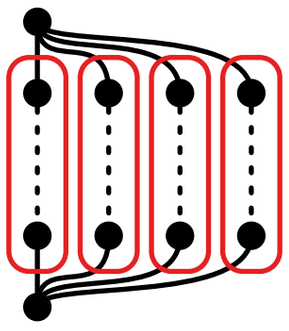

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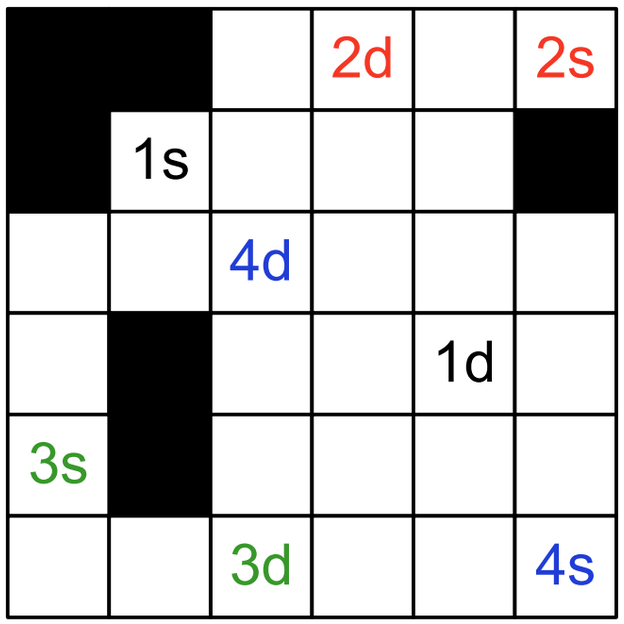


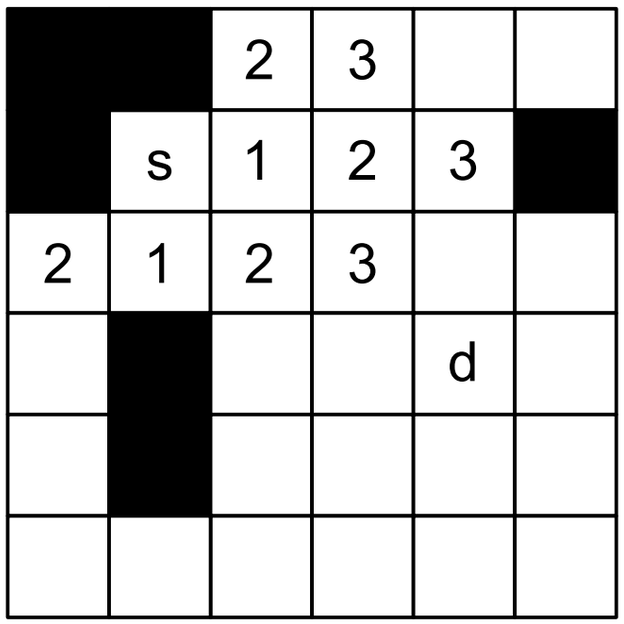


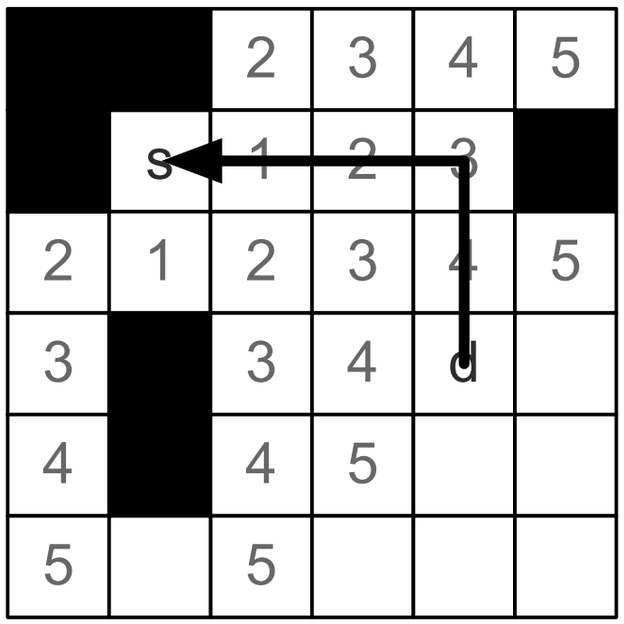


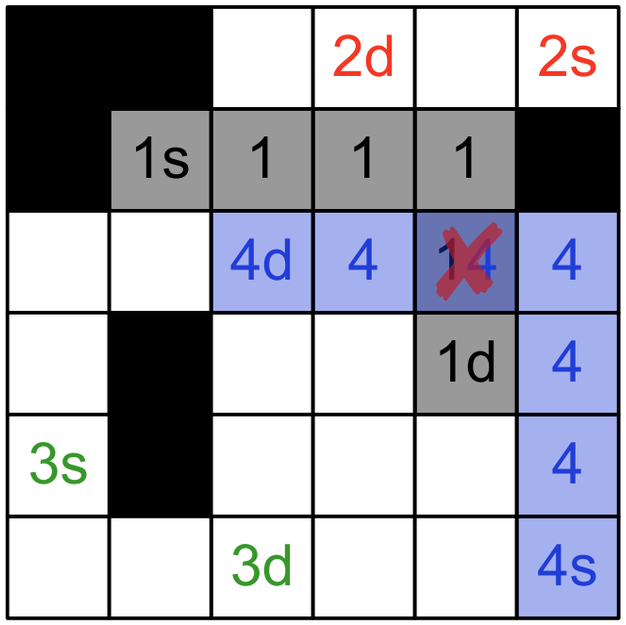


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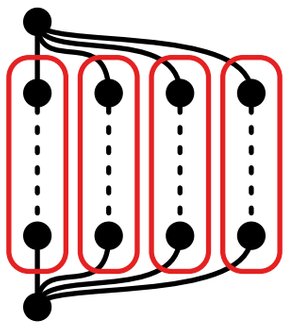

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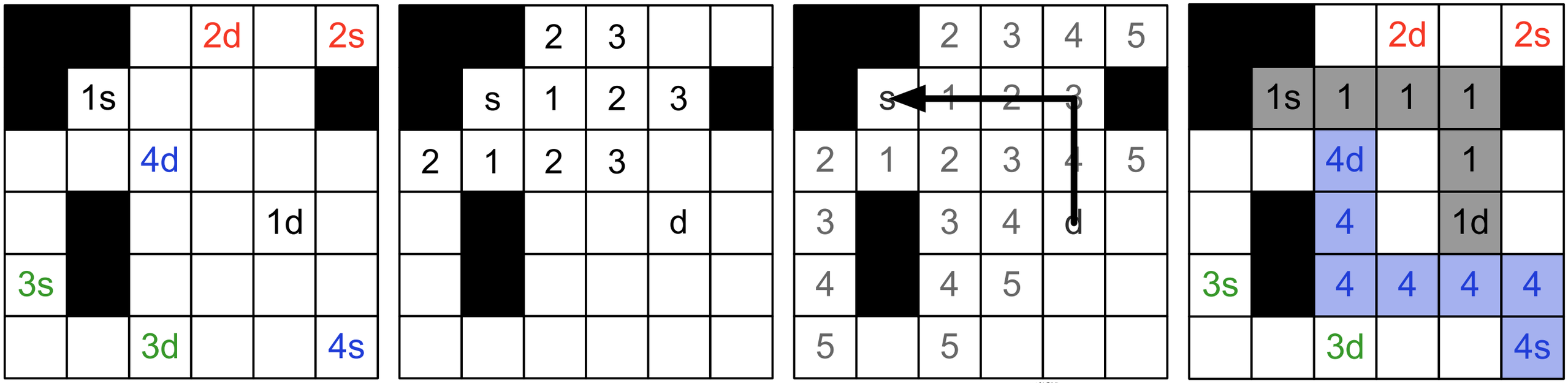


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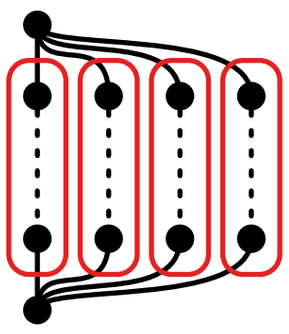
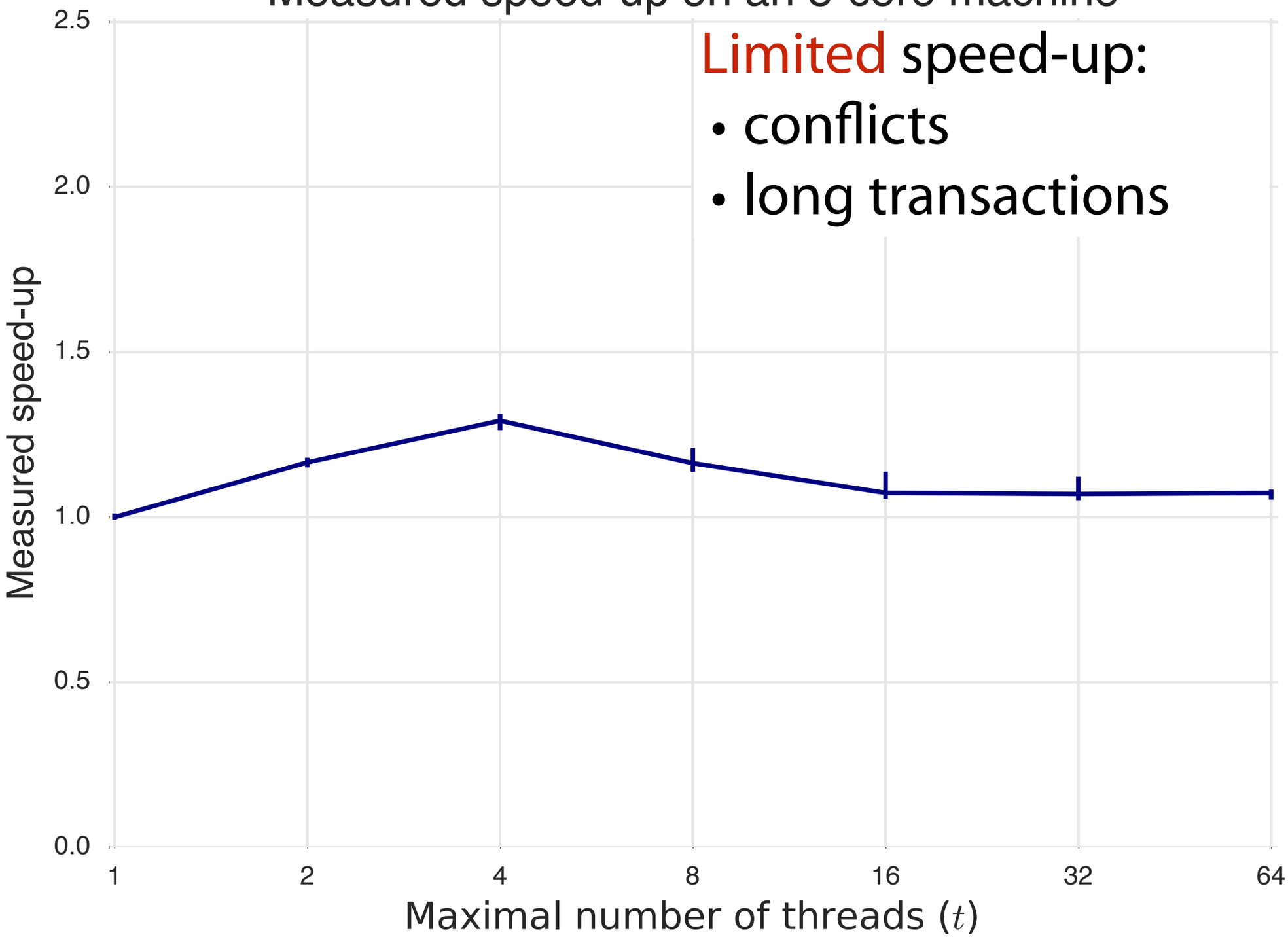
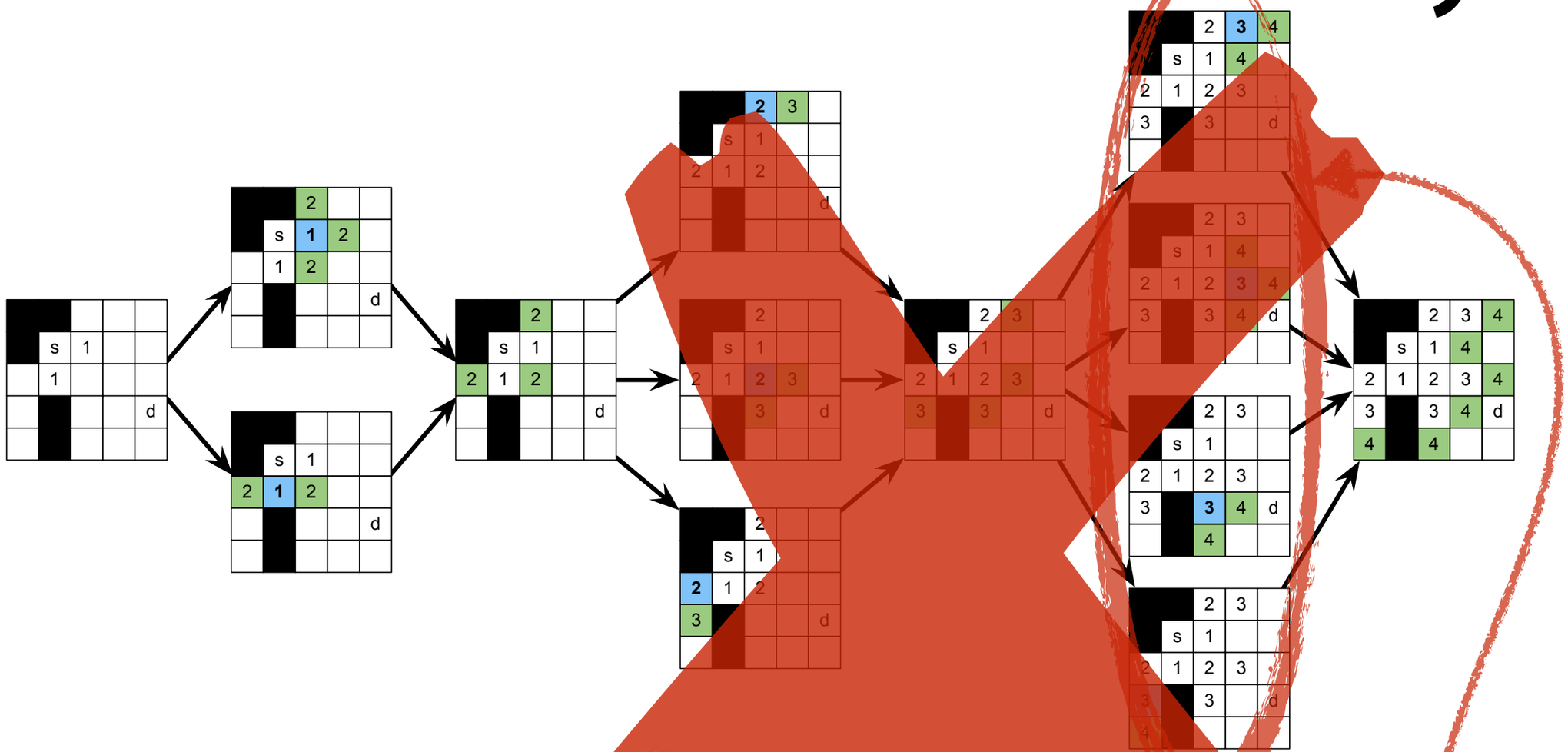


# Labyrinth has limited speed-up



# Parallel search in Labyrinth




expand
in parallel

```
(for [[src dst] input-pairs]
  (fork
    (atomic
      (let [local-grid (copy grid)]
        (expand src dst local-grid)
        (add-path grid
          (traceback local-grid dst))))))
```

```
(defn expand [src dst
  (loop [q #{src}]
    (if (empty? q
      false
      (if (contains? q dst)
        true
        (recur
          (expand-step q
```

```
(defn expand-step [q grid]
  (reduce union #{}
    (pmap
      (fn [p] (expand-point p grid))
      q)))
```

parallel breadth-first search

Does **not** work!

# Problems when creating threads in a transaction

- Threads in transaction do not share context (Clojure, ScalaSTM)

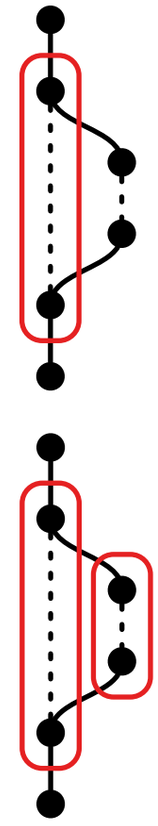
  ⇒ **no access to transactional state**

  or

  ⇒ **serializability violated**

```
(atomic
  (fork
    (ref-set …)))
```

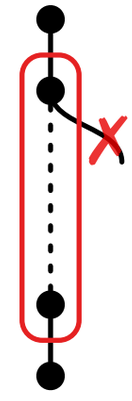
```
(atomic
  (fork
    (atomic
      (ref-set …))))
```



- Threads in transaction prohibited (Haskell)

  ⇒ **parallelism limited**

```
atomically $
  do { forkIO … }
```



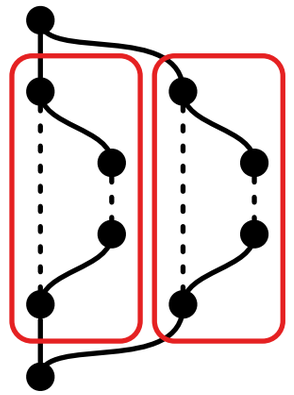
# Transactional Tasks

**Parallelism in transaction**

⇒ Transactional task = thread created in transaction

Task can **access transactional variables**

⇒ Task adopts encapsulating transactional context



**Isolation** between tasks

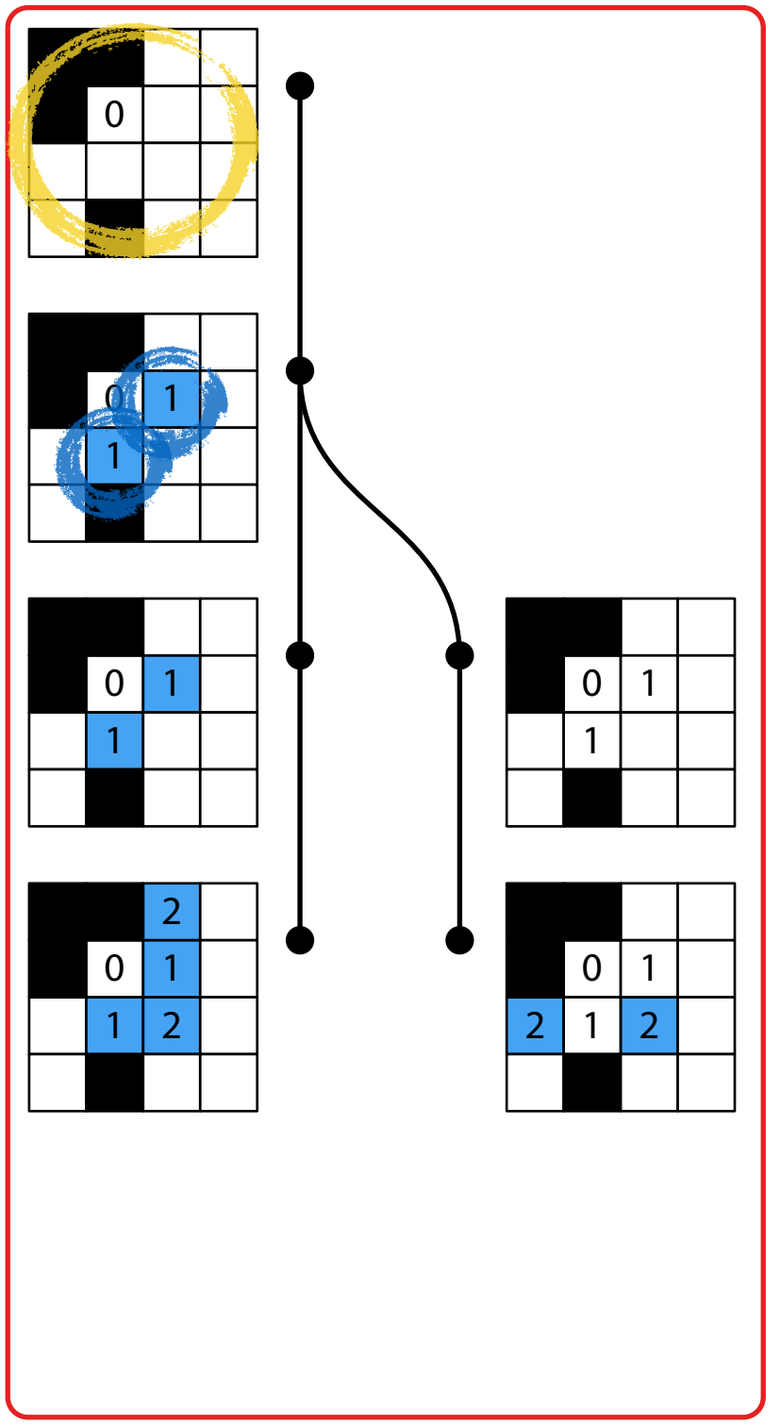
⇒ Tasks work on conceptual copy

**Serializability**

⇒ All tasks should join before transaction commits

On conflict, *all* tasks abort

# Task = snapshot + store




```
(atomic
  (ref-set … 1)
```

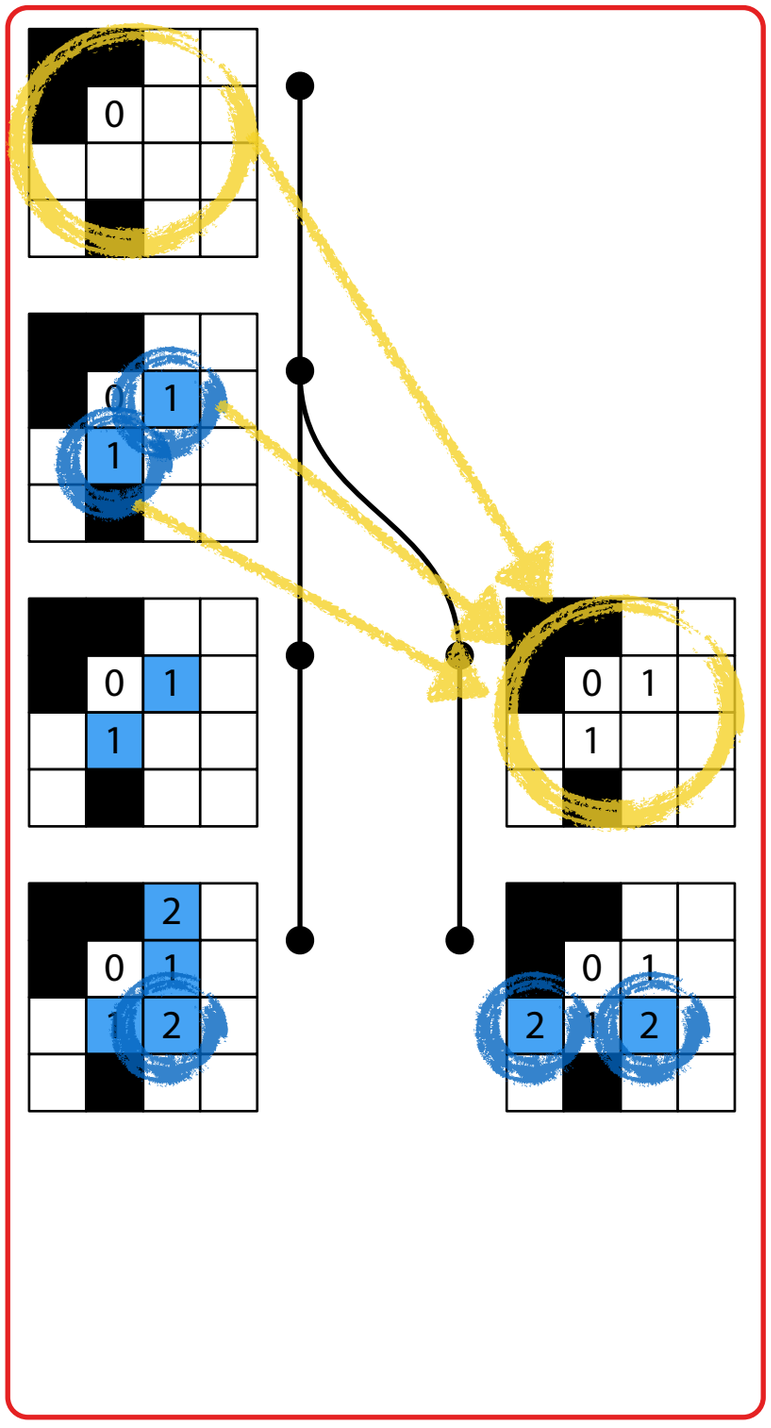
Each transactional task contains:

**snapshot σ**: transactional state on creation

**local store τ**: local modifications

$$\begin{aligned} & \mathrm{T_x} \uplus \langle f_p, \sigma, \tau, \mathrm{F_s}, && \mathrm{F_j}, \mathcal{E}[\texttt{fork}\ e] \rangle \\ \Rightarrow_{\mathrm{tf}}\ & \mathrm{T_x} \uplus \langle f_p, \sigma, \tau, \mathrm{F_s} \uplus \{f'\}, \mathrm{F_j}, \mathcal{E}[f_c] && \rangle \uplus \langle f_c, \sigma :: \tau, \varnothing, \varnothing, \mathrm{F_j}, e \rangle \\ & \text{with } f_c \text{ fresh} \end{aligned}$$

# `fork` creates isolated task




```
(atomic
  (ref-set … 1)
  (fork
    (ref-set … 2))
  (ref-set … 2)
```

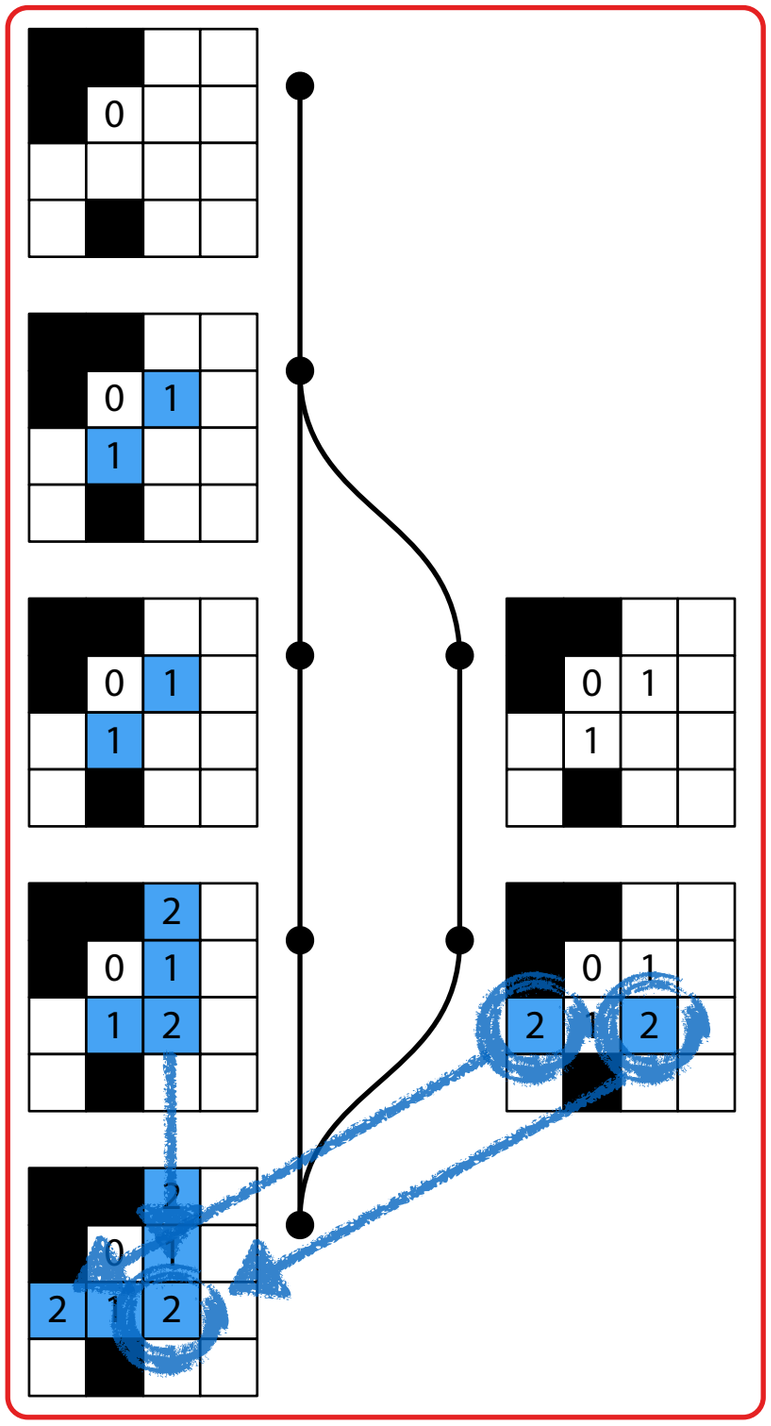
Each transactional task contains:

**snapshot σ**: transactional state on creation

**local store τ**: local modifications

$$\mathrm{T_x} \cup \langle f_p, \sigma, \tau, \mathrm{F_s}, \quad \mathrm{F_j}, \mathcal{E}[\texttt{fork}\ e] \rangle$$
$$\Rightarrow_{\mathrm{tf}} \mathrm{T_x} \cup \langle f_p, \sigma, \tau, \mathrm{F_s} \cup \{f'\}, \mathrm{F_j}, \mathcal{E}[f_c] \rangle \cup \langle f_c, \sigma :: \tau, \varnothing, \varnothing, \mathrm{F_j}, e \rangle$$
with $f_c$ fresh

# `join` merges changes




```
(atomic
  …
  (join child))
```

## merge local store $\tau'$ of child into parent

$$\mathrm{T_x} \cup \langle f_p, \sigma, \tau, \mathrm{F_s}, \mathrm{F_j}, \mathcal{E}[\texttt{join}\ f_c] \rangle \cup \langle f_c, \sigma', \tau', \mathrm{F'_s}, \mathrm{F'_j}, v \rangle$$
$$\Rightarrow_{\mathrm{tf}} \mathrm{T_x} \cup \langle f_p, \sigma, \tau :: \tau', \mathrm{F_s} \cup \mathrm{F'_s} \cup \mathrm{F_j} \cup \mathrm{F'_j} \cup \{f_c\}, \mathcal{E}[v] \rangle \cup \langle f_c, \sigma', \tau', \mathrm{F'_s}, \mathrm{F'_j}, v \rangle$$
$$\text{if } f_c \notin \mathrm{F_j} \text{ and } \mathrm{F'_s} \subseteq \mathrm{F'_j}$$

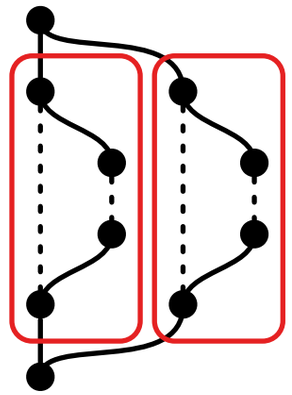
## Conflict resolution function:

```
(ref 0 resolve)

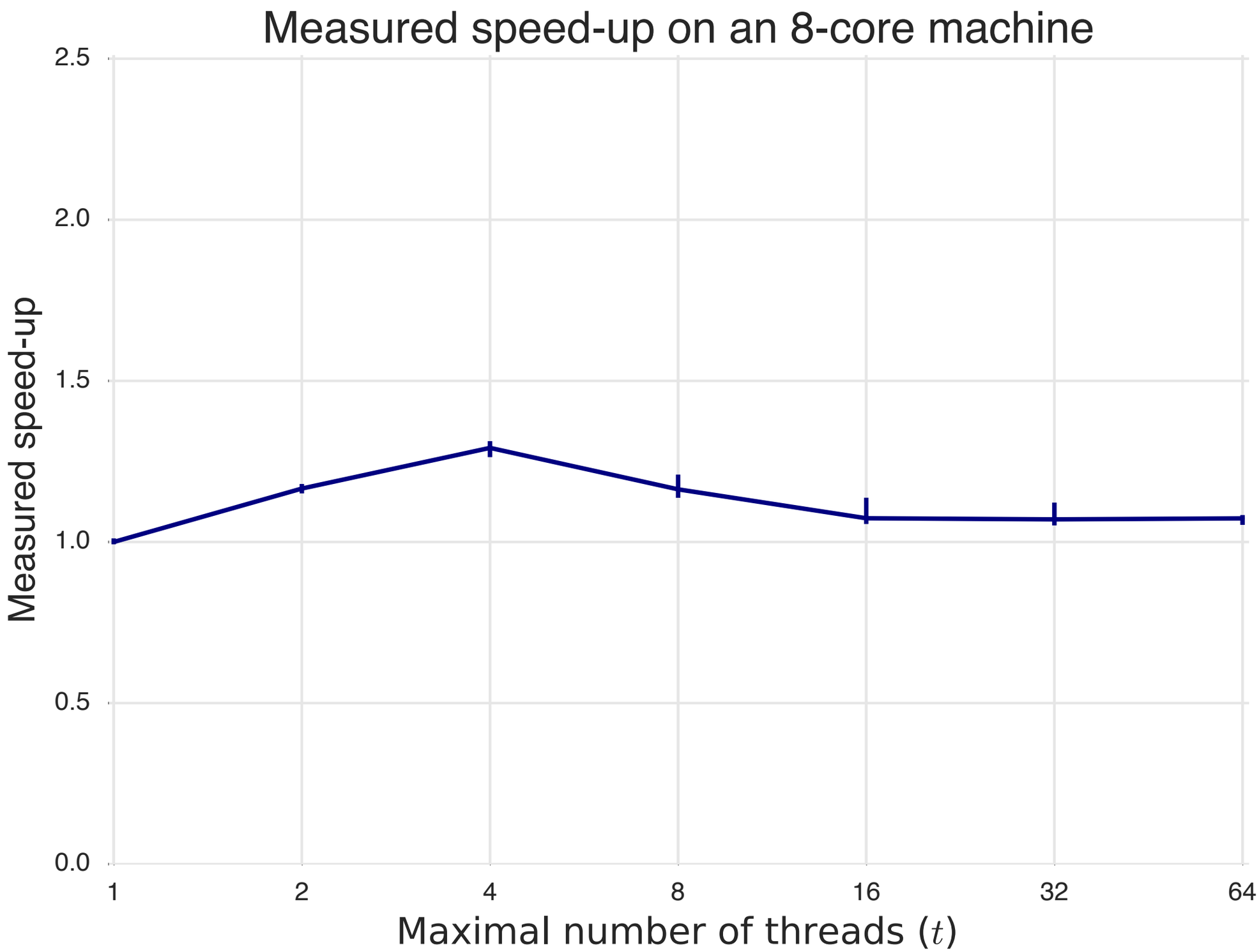
(defn resolve [o p c] (min p c))
(defn resolve [o p c] c)
(defn resolve [o p c]
  (error "merge conflict"))
```

# Properties of transactional tasks

- **In-transaction parallelism** possible
- **Serializability** of transactions
- **Coordination** of tasks: all or none
- In-transaction **determinacy**

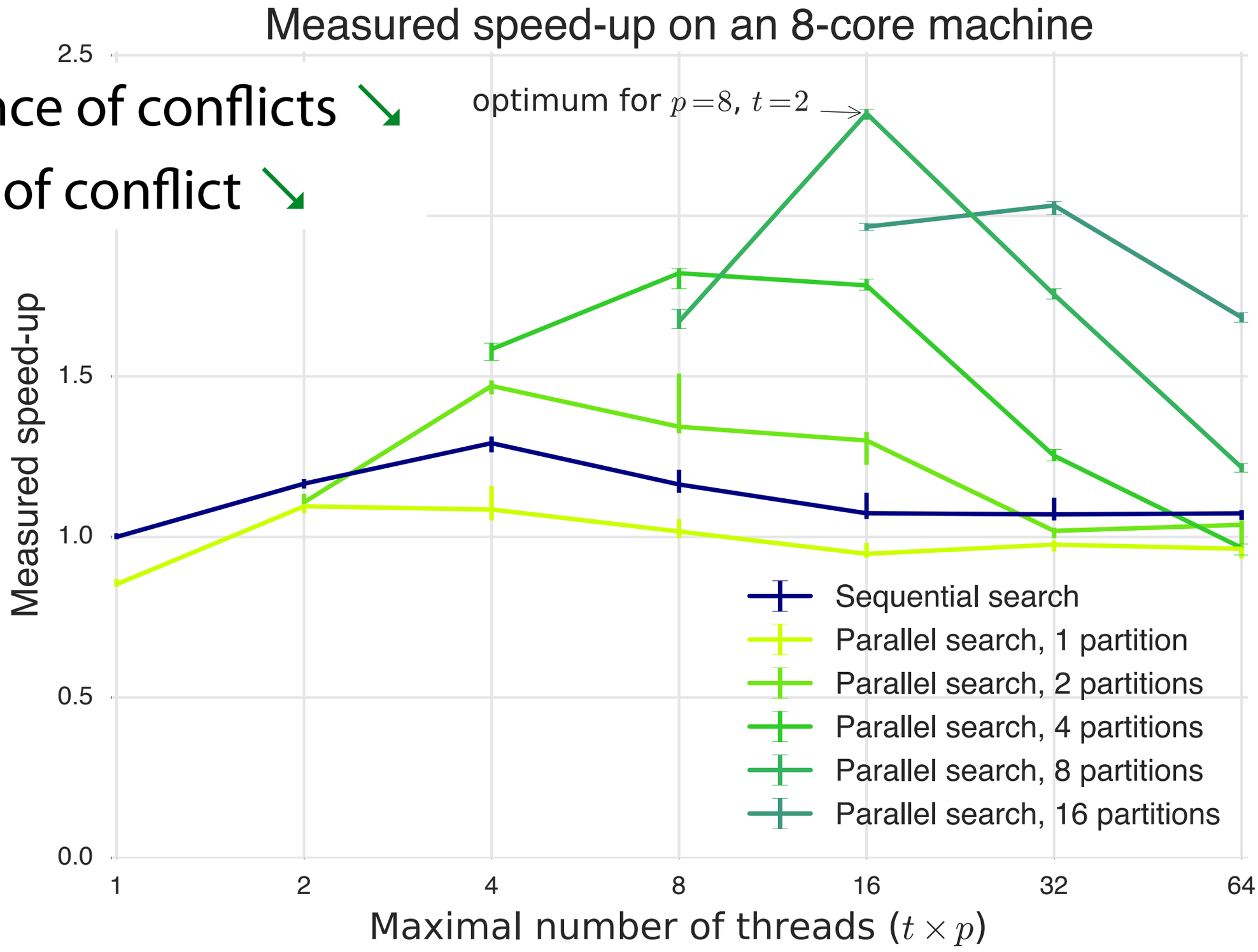


# Evaluation: Labyrinth



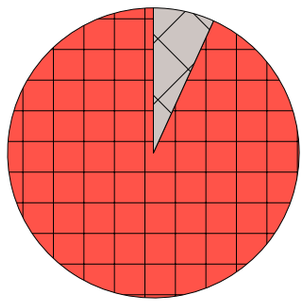
# Evaluation: Labyrinth

- Chance of conflicts ↘
- Cost of conflict ↘



# Evaluation: Bayes

Time spent
in transaction
(in learning phase)

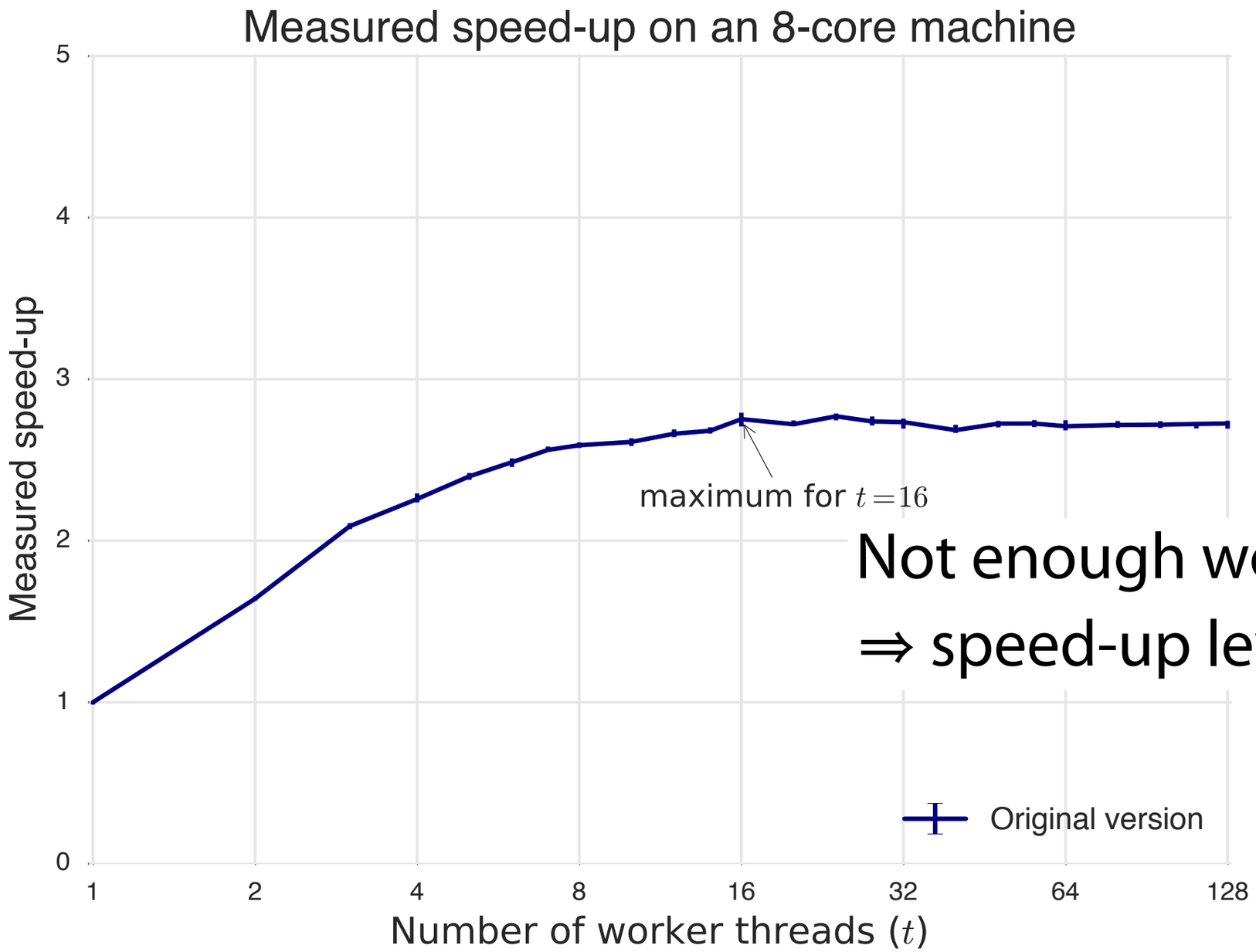


Transactional (93.2%)

Non-transactional (6.8%)

```
(atomic
  …
  (for [from-id (range (:n-var adtree))]

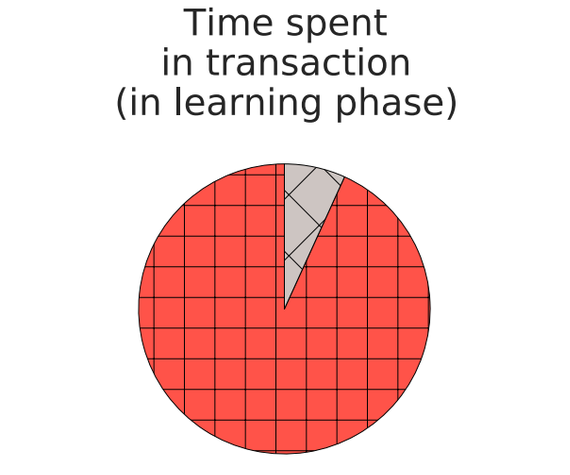
      (compute-local-log-likelihood …)))
```



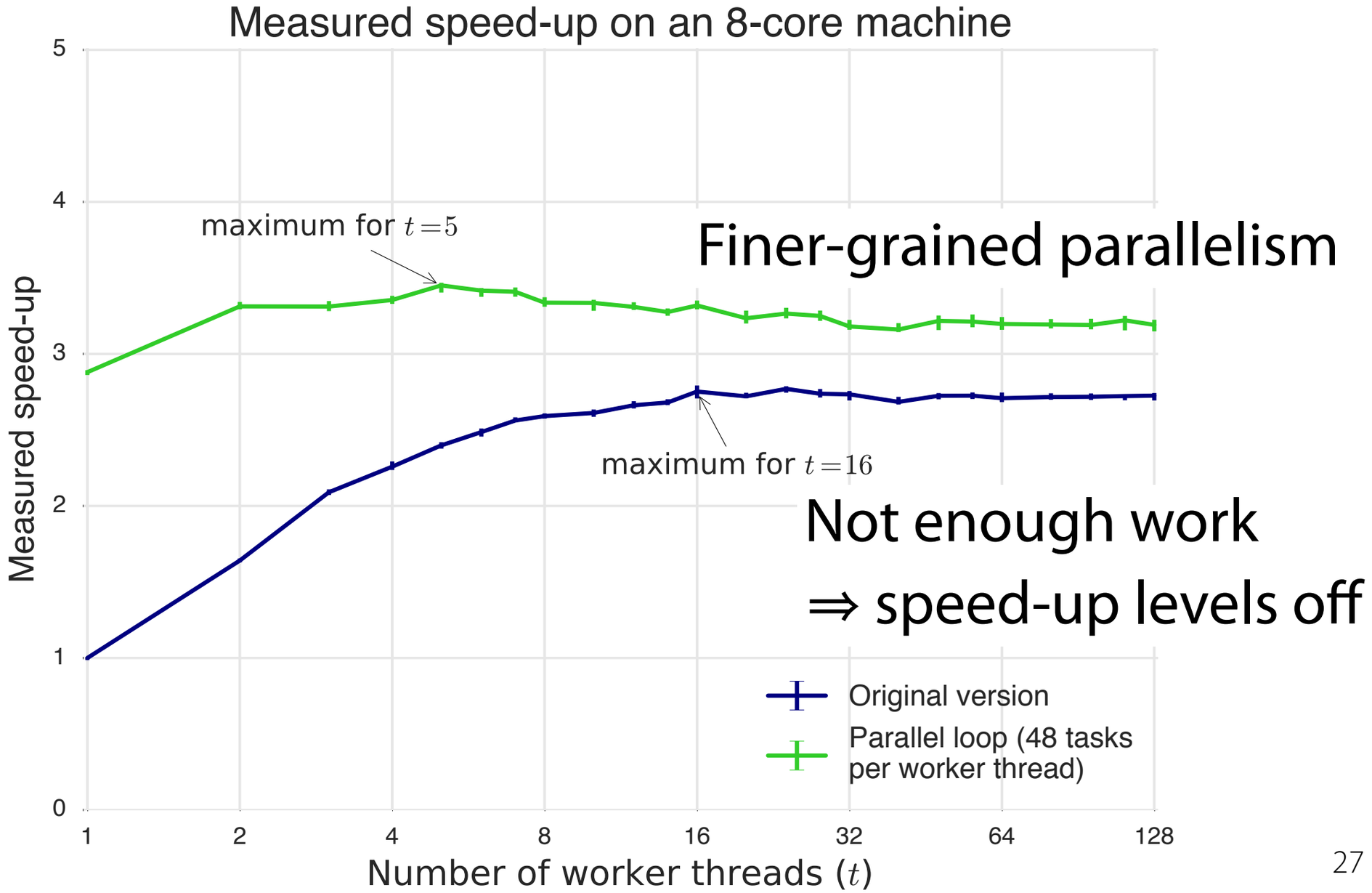

Not enough work

⇒ speed-up levels off

# Evaluation: Bayes




```
(atomic
  …
  (for [from-id (range (:n-var adtree))]
    (fork
      (compute-local-log-likelihood …))))
```




Finer-grained parallelism

Not enough work

⇒ speed-up levels off

# Insights from experiments

- Labyrinth: parallelize search algorithm
  ⇒ fewer & cheaper conflicts

- Bayes: more fine-grained parallelism
  ⇒ better exploit hardware

- Low developer effort (re-use existing concepts)

- Suitable for applications with long transactions

# Implementation

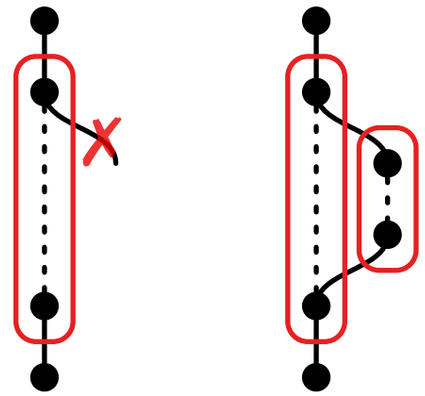
Fork of Clojure

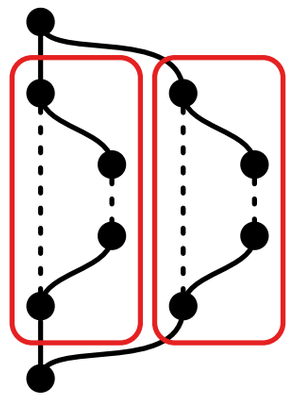
https://github.com/jswalens/transactional-futures/

http://soft.vub.ac.be/~jswalens/ecoop-2016-artifact/

# Summary

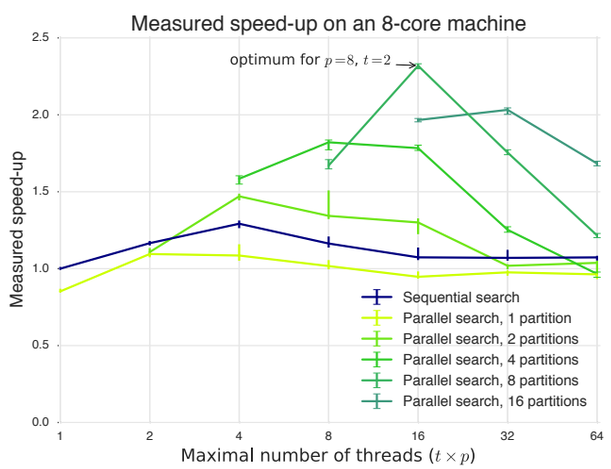
**Parallelism in a transaction** is useful
for programs with **long transactions**
But currently:
↗ **not allowed** (Haskell)
↘ **not serializable** (Clojure, Scala)





Idea: **transactional tasks**
- safe access to encapsulating transaction
- serializable, coordinated, determinate

Benefits:
- finer-grained parallelism ⇒ speed-up
- low developer effort




More details:
- J. Swalens et al. "Transactional Tasks: Parallelism in Software Transactions", ECOOP 2016
- https://github.com/jswalens/transactional-futures/

# Transactional Tasks vs. Nested Parallel Transactions

Guarantees in transaction

- NPT: `(atomic (fork …))` → race conditions possible
- NPT: `(atomic (fork (atomic …)))` → serializable, last writer wins (not deterministic)
- TT: conflict resolution → *in-transaction determinacy* (but may need to define resolution function)

Performance

- NPT: roll back and retry subtransaction
- TT: resolve conflict

→ different performance characteristics depending on application (chance of conflicts between threads in tx)

More fine-tuned conflict resolution (e.g. minimum for Labyrinth)

# STAMP

| Application | Instructions /tx (mean) | Time in tx |
|---|---|---|
| labyrinth | 219,571 ● | 100% ● |
| bayes | 60,584 ● | 83% ● |
| yada | 9,795 ● | 100% ● |
| vacation-high | 3,223 ◐ | 86% ● |
| genome | 1,717 ◐ | 97% ● |
| intruder | 330 ○ | 33% ◐ |
| kmeans-high | 117 ○ | 7% ○ |
| ssca2 | 50 ○ | 17% ○ |

**Coarse-grained parallelism**
between parts of the application

**Fine-grained parallelism**
within a part of the application

## Transactions

- Conflicts span multiple variables
- Difficult to define conflict resolution functions
- Chance of conflicts depends on application

⇒ resolve high-level conflicts using serializability

## Transactional tasks

- Conflict affects single variable
- Define conflict resolution function based on algorithm
- Conflicts likely, so rollback bad for performance

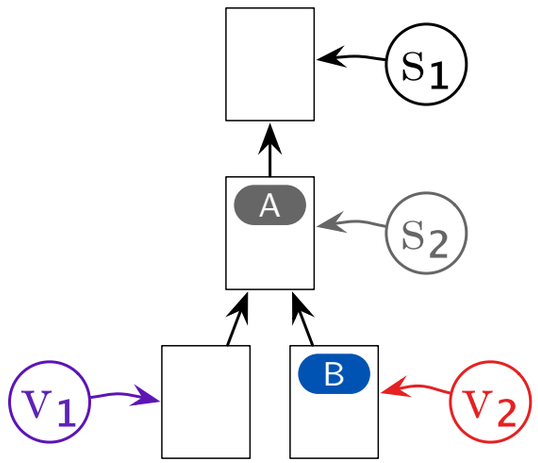
⇒ resolve low-level conflicts using conflict resolution functions

# Implementation details

**(a)** Code example.

```
(atomic
  [1](ref-set gray A)
  [2](fork [3](ref-set blue B)
           [4](fork [5](ref-set green C))
           [6](ref-set red D)
           ...)
  [7](ref-set purple E)
  ...)
```

**(b)** Data after step 3.




**(c)** Data after step 7.