Exercise Session 13

Data Structures and Algorithms, D-MATH, ETH Zurich

Program of today

Feedback of last exercise

Repetition theory

Next Exercise

1. Feedback of last exercise

Exercise: Sum of a vector

```
void sum_par( Iterator beg, Iterator end, int& result ) {
  const int nThreads = std::thread::hardware_concurrency();
  std::vector<std::thread> myThreads;
  std::vector<int> sums( nThreads, 0 );
  const int partSize = (end-beg)/nThreads;

  for( int i=0; i<nThreads-1; ++i ){
    myThreads.emplace_back(
      std::thread(sum_ser, beg, beg + partSize, std::ref(sums[i])));
    beg += partSize;
  }
  // ...
  for( auto& t:myThreads ) t.join();
  sum_ser( sums.begin(), sums.end(), result );
}
```

Exercise: Sum of a vector

```
void sum_ser(
    Iterator from,
    Iterator to,
    int& result ) {

  int local = 0;
  for( ;from != to; ++from )
    local += *from;
  result = local;
}
```

```
void sum_ser(
    Iterator from,
    Iterator to,
    int& result ) {

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Difference?

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Difference?

execution time: 0.468879 ms

execution time: 0.944031 ms

Exercise: Sum of a vector – False Sharing!

```
void sum_ser(
    Iterator from,
    Iterator to,
    int& result ) {

  int local = 0;
  for( ;from != to; ++from )
    local += *from;
  result = local;
}
```

```
void sum_ser(
    Iterator from,
    Iterator to,
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  result = 0;
  for( ;from != to; ++from )
    result += *from;
}
```

Difference?

execution time: 0.468879 ms

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Exercise: Mergesort (2-threads)

```
void mergesort_par( std::vector<int> & v ) {
  int n = v.size();
  int partSize = n / 2;

  std::thread t1( mergesort, std::ref(v), 0, partSize-1 );
  std::thread t2( mergesort, std::ref(v), partSize, n-1 );
  t1.join();
  t2.join();
  merge( v, 0, partSize-1, n-1 );
}
```

analogously with n threads

Exercise: Mergesort Recursively

```
void mergesort_par(std::vector<int> & v, int cutoff, int l, int r) {
  if (r-l < cutoff){ // sequential base case
    mergesort( v, l, r );
  } else {
    int m = ( l+r )/2 ;
    std::thread t (mergesort_par,std::ref(v),cutoff,l,m);
    mergesort_par(v,cutoff,m+1,r); // avoid forking another thread
    t.join();
    merge(v,l,m,r);
  }
}
```

2. Repetition theory

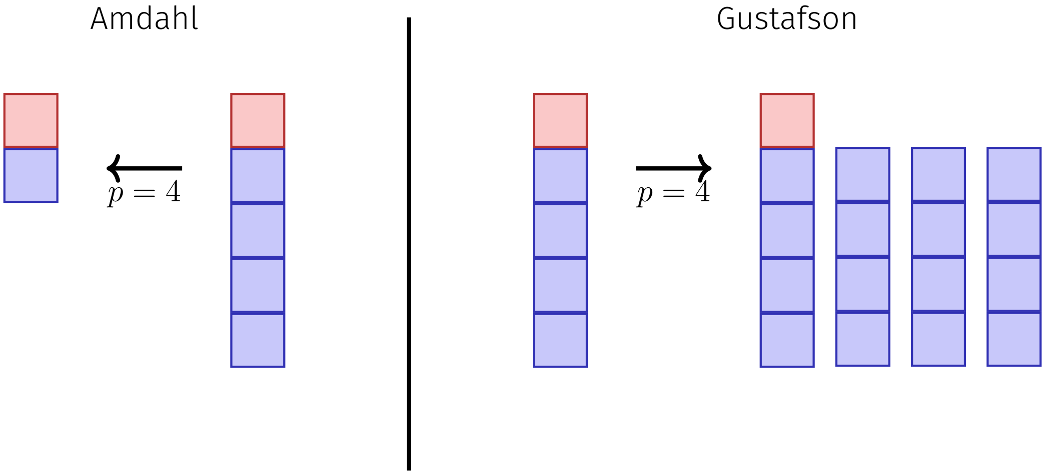
Parallel Performance

Given

- fixed amount of computing work W (number computing steps)
- Sequential execution time T_1
- Parallel execution time on p CPUs

	runtime	speedup	efficiency
perfection (linear)	$T_p = T_1/p$	$S_p = p$	$E_p = 1$
loss (sublinear)	$T_p > T_1/p$	$S_p < p$	$E_p < 1$
sorcery (superlinear)	$T_p < T_1/p$	$S_p > p$	$E_p > 1$

Amdahl vs. Gustafson



Amdahl vs. Gustafson, or why do we care?

Amdahl	**Gustafson**
pessimist	optimist
strong scaling	weak scaling

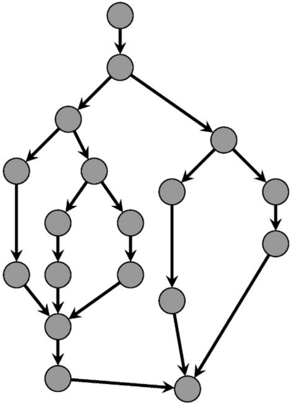
Amdahl vs. Gustafson, or why do we care?

Amdahl	**Gustafson**
pessimist	optimist
strong scaling	weak scaling

$\Rightarrow$ need to develop methods with small sequential protion as possible.

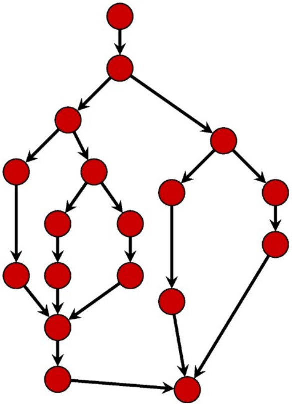
Task Parallelism: Performance Model

- p processors
- Dynamic scheduling
- T_p: Execution time on p processors



Performance Model

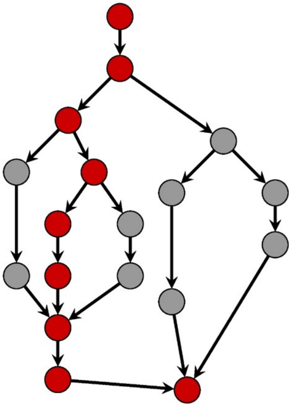
- T_p: Execution time on p processors
- T_1: **work**: time for executing total work on one processor
- T_1/T_p: Speedup



Performance Model

- T_∞: **span**: critical path, execution time on ∞ processors. Longest path from root to sink.
- T_1/T_∞: **Parallelism:** wider is better
- Lower bounds:

$$T_p \geq T_1/p \quad \text{Work law}$$
$$T_p \geq T_\infty \quad \text{Span law}$$



Greedy Scheduler

Greedy scheduler: at each time it schedules as many as availbale tasks.

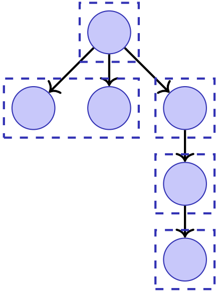
Theorem 1

On an ideal parallel computer with p processors, a greedy scheduler executes a multi-threaded computation with work T_1 and span T_∞ in time

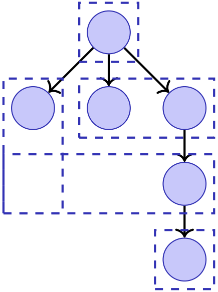
$$T_p \leq T_1/p + T_\infty$$

Beispiel

Assume $p = 2$.



$T_p = 5$



$T_p = 4$

Race Conditions

Data Race (low-level Race-Conditions) Erroneous program behavior caused by insufficiently synchronized accesses of a shared resource by multiple threads, e.g. Simultaneous read/write or write/write of the same memory location

Bad Interleaving (High Level Race Condition) Erroneous program behavior caused by an unfavorable execution order of a multithreaded algorithm, even if that makes use of otherwise well synchronized resources.

Memory Models

When and if effects of memory operations become visible for threads, depends on hardware, runtime system and programming language.

A **memory model** (e.g. that of C++) provides minimal guarantees for the effect of memory operations

- leaving open possibilities for optimisation
- containing guidelines for writing thread-safe programs

For instance, C++ provides **guarantees when synchronisation with a mutex** is used.

Counter Problem

```
std::vector<std::thread> tv(10);
int counter {0};
for (auto & t:tv)
  t = std::thread([&]{
    for (int i =0; i<100000; ++i){counter++;} // race!!
  });
for (auto & t:tv)
  t.join();
std::cout << "count= "<< counter << std::endl;
```

Counter Solution 1

```
std::vector<std::thread> tv(10);
std::mutex lock;
int counter {0};
for (auto & t:tv)
  t = std::thread([&]{
  for (int i =0; i<100000; ++i){
    mutex.lock(); counter++; mutex.unlock(); // synchronized!
  }});
for (auto & t:tv)
  t.join();
std::cout << "count= "<< counter << std::endl;
```

Counter Solution II

```
std::vector<std::thread> tv(10);
std::atomic<int> counter {0};
for (auto & t:tv)
  t = std::thread([&]{
    for (int i =0; i<100000; ++i){counter++;} // atomic!!
  });
for (auto & t:tv)
  t.join();
std::cout << "count= "<< counter << std::endl;
```

Quiz:What's wrong with this code?

```
void exchangeSecret(Person & a, Person & b) {
  a.getMutex()->lock();
  b.getMutex()->lock();
  Secret s = a.getSecret();
  b.setSecret(s);
  a.getMutex()->unlock();
  b.getMutex()->unlock()
}
```

Deadlock

Thread 1:

```
exchangeSecret(p1, p2);
```

Thread 2:

```
exchangeSecret(p2, p1);
```

Deadlock

Thread 1:
```
exchangeSecret(p1, p2);
```

Thread 2:
```
exchangeSecret(p2, p1);
```

How to resolve?

Possible Solution

```
void exchangeSecret(Person & a, Person & b) {
  std::mutex* first;
  std::mutex* second;
  if (a.name < b.name){
    first = a.getMutex(); second = b.getMutex();
  } else {
    first = b.getMutex(); second = a.getMutex();
  }
  first->lock();
  second->lock();
  Secret s = a.getSecret();
  b.setSecret(s);
  first->unlock();
  second->unlock();
}
```

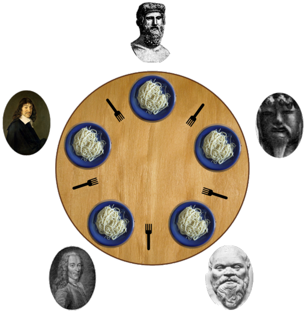
Deadlocks and Races

- Not easy to spot
- Hard to debug
- Might happen only very rarely
- Testing usually not good enough
- Reasoning about code is required

Lesson learned: Need to be careful when programming with locks!

3. Next Exercise

Dining Philosophers



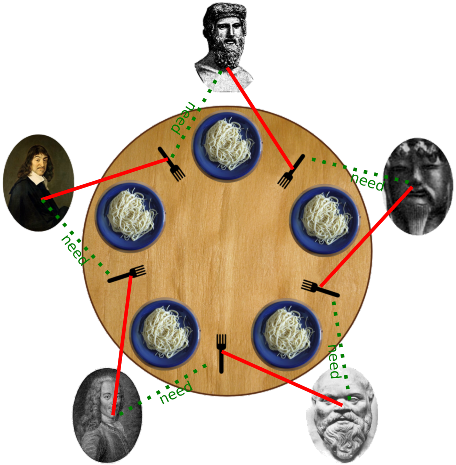
- Philosophers only think and eat. Each needs two forks to eat.
- Philosophers = threads, forks = locks.

Dining Philosophers - pseudocode

```
while(true) {
    think();
    acquire_fork_on_left_side();
    acquire_fork_on_right_side();
    eat();
    release_fork_on_right_side();
    release_fork_on_left_side();
}
```

- Problems with this code?

Dining Philosophers - deadlock



- Solutions?

Dining Philosophers

- Resolve cyclic dependency
- For instance: Philosoph five takes first the **right** fork.
- General solution: Define lock order. Then, always lock in that order.