Locks & barriers (week 2)

INF4140 - Models of concurrency

Locks & barriers, lecture 2

Høsten 2013

2. 9. 2013

Mandatory assignment 1 (“oblig”)

- Deadline: Friday September 27 at 18.00
- Possible to work in pairs
- Online delivery (Devilry): https://devilry.ifi.uio.no

- Central to the course are general mechanisms and issues related to parallel programs
- **Previous class:** *await language* and a simple version of the *producer/consumer* example

Today

- Entry- and exit protocols to the *critical section*
  - Protect reading and writing to *shared variables*
- *Barriers*
  - Iterative algorithms:
    Processes must *synchronize* between each iteration
  - Coordination using *flags*

```
int buf, p := 0; c := 0;
```

```
process Producer {
  int a[N];...
  while (p < N) {
   < await (p = c) ; >
    buf := a[p];
      p := p+1;
 }
}
```

```
process Consumer {
int b[N];...
while (c < N) {
 < await (p > c) ; >
  b[c] := buf;
      c := c+1;
  }
}
```

Invariants

- global: $c \leq p \leq c + 1$
- local (in the producer): $0 \leq p \leq n$

An invariant holds in *all states* in all histories of the program.

Critical section

- fundamental for concurrency
- immensely intensively researched, many solution
- crit. sec.: one part of a program that is/needs to be "protected" agains interference by other processes
- execution under *mutal exclusion*
- related to "atomicity"

Main question here

How can we implement critical sections / conditional critical sections?

- various solutions and properties/guarantees
- using *locks* and low-level operations
- SW-only solutions? HW or OS support?
- active waiting (later semaphores and passive waiting)

Access to Critical Section (CS)

- Several processes compete for access to a shared resource
- Only one process can have access at a time: "mutual exclusion" (mutex)
- Possible examples:
  - Execution of bank transactions
  - Access to a printer
- A solution of the CS problem can be used to *implement* **await**-statements

Operations on shared variables happen inside the CS.
Access to the CS must then be protected to prevent interference.

Listing 1: General pattern for CS

```
process p[i=1 to n] {
  while (true) {
    CSentry          # entry protocol to CS
    CS
    CSexit           # exit protocol from CS
    non-CS
  }
}
```

- Assumption: A process which enters the CS will eventually leave it.

⇒ programming advice: be aware of exceptions inside CS!

Naive solution

```
int in = 1          # possible values in {1,2}
```

```
process p1 {                        process p2 {
  while (true) {                      while (true) {
    while (in=2) {skip};                while (in=1) {skip};
    CS;                                 CS;
    in := 2;                            in := 1
    non-CS                              non-CS
  }
```

- entry-protocol: active/busy waiting
- exit protocol: atomic assignment

Good solution? A solution at all? What's good, what's less so?

Naive solution

```
int in = 1          # possible values in {1,2}

process p1 {                    process p2 {
  while (true) {                  while (true) {
    while (in=2) {skip};            while (in=1) {skip};
    CS;                             CS;
    in := 2;                        in := 1
    non-CS                          non-CS
  }
```

- entry-protocol: active/busy waiting
- exit protocol: atomic assignment

Good solution? A solution at all? What's good, what's less so?

- More than 2 processes?
- Different execution times?

Mutual exclusion (Mutex): At any time, at most one process is inside CS.

Absence of deadlock: If all processes are trying to enter CS, at least one will succeed.

Absence of unnecessary delay: If some processes are trying to enter CS, while the other processes are in their non-critical sections, at least one will succeed.

Eventual entry: A process attempting to enter CS will eventually succeed.

NB: The three first are safety properties,[1] the last a liveness property. (SAFETY: no bad state – LIVENESS: something good will happen.)

[1] point 2 and 3 are slightly up-to discussion/standpoint!

Safety: Invariants (review)

A safety property expresses that a program does not reach a "bad" state. In order to prove this, we can show that the program will never leave a "good" state:

- Show that the property holds in all initial states
- Show that the program statements preserve the property

Such a (good) property is usually called a *global invariant*.

Atomic sections

Used for synchronization of processes

- General form:

$$< \texttt{await(B) S;} >$$

  - `B`: Synchronization condition
  - Executed atomically when `B` is true
- Unconditional critical section (`B` is **true**):

$$< \texttt{S;} >$$

  `S` executed atomically
- Conditional synchronization:[2]

$$< \texttt{await(B);} >$$

[2] We also use then just `await`(B) or maybe `await`B. But also in this case we assume that B is evaluated atomically.

Critical sections using locks

```
bool lock = false;

process [i=1 to n] {
  while (true) {
    < await (¬ lock) lock := true >;
    CS;
    lock := false;
    non CS;
  }
}
```

Safety properties:

- Mutex
- Absence of deadlock
- Absence of unnecessary waiting

What about taking away the angle brackets <...>?

Test & Set is a method/pattern for implementing *conditional atomic action*:

```
TS(lock) {
  < bool initial := lock;
  lock := true >;
  return initial
}
```

- effect of `TS(lock)`
  - side effect: The variable `lock` will always have value `true` after `TS(lock)`,
  - returned value: `true` or `false`, depending on the original state of lock
  - exists as an *atomic* HW instruction on many machines.

```
bool lock := false;

process p [i=1 to n] {
  while (true) {
    while (TS(lock)) {skip};          # entry protocol
    CS
    lock := false;                    # exit protocol
    non−CS
  }
}
```

NB: Safety: Mutex, absence of deadlock and of unnecessary delay.
strong fairness needed

A puzzle: "paranoid" entry protocol

better safe than sorry?

What about *double-checking* in the entry protocol whether it is *really, really* safe to enter?

```
bool lock := false;

process p[i = i to n] {
  while (true) {
    while (lock) {skip};     # additional spin-lock check
    while (TS(lock)) {skip};

    CS;
    lock := false;
    non-CS
  }
}
```

Does that make sense?

A puzzle: "paranoid" entry protocol

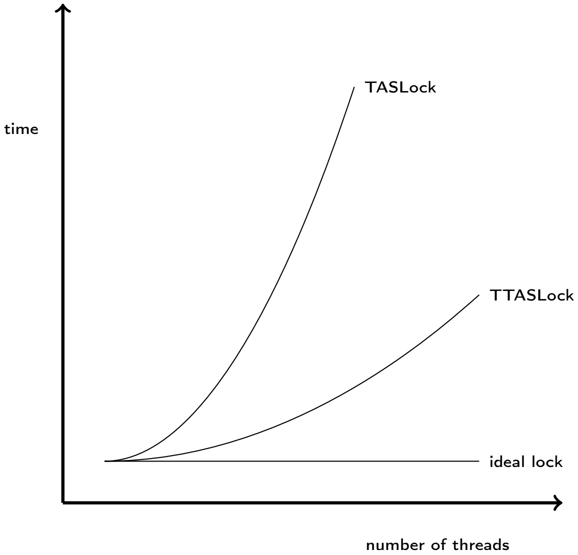
better safe than sorry?

What about *double-checking* in the entry protocol whether it is *really, really* safe to enter?

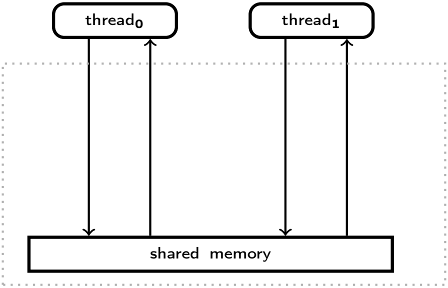
```
bool lock := false;

process p[i = i to n] {
  while (true) {
    while (lock) {skip};       # additional spin lock check
    while (TS(lock)) {
      while (lock) {skip}};    # + more inside the TAS loop
    CS;
    lock := false;
    non—CS
  }
}
```

Does that make sense?

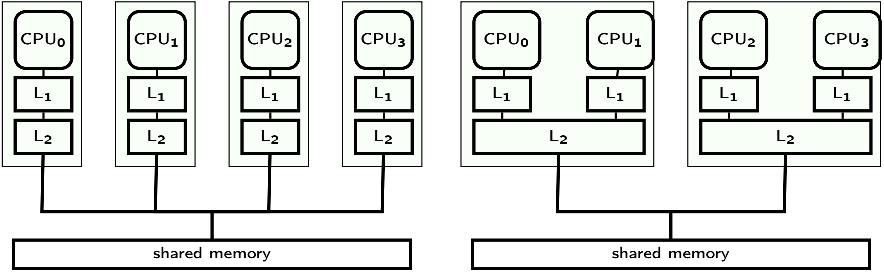
Performance under load (contention)



A glance at HW for shared memory



A glance at HW for shared memory



Test and test & set

- test-and-set operation:
  - (powerful) HW instruction for synchronization
  - accesses main memory (and involves "cache synchronization")
  - much slower than cache access
- spin-loops: faster than TAS loops
- "double-checked locking": important design pattern/programming idiom for efficient CS (under certain architectures)[3]

[3]depends on the HW architecture/memory model. In some architectures: does not guarantee mutex! in which case it's an anti-pattern . . .

Let CSentry and CSexit implement entry- and exit-protocols to the critical section.
Then the statement < S;> can be implemented by

```
CSentry; S; CSexit;
```

Implementation of *conditional critical section* < await (B) S;> :

```
CSentry;
  while (!B) {CSexit ; CSentry};
  S;
CSexit;
```

The implementation can be optimized with Delay between the exit and entry in the body of the while statement.

What about Liveness?

So far: no(!) solution for "Eventual Entry"-property, except the very first (which did not satisfy "Absence of Unnecessary Delay").

- Liveness: Something good will happen
- Typical example for sequential programs: (esp. in our context) Program termination[4]
- Typical example for parallel programs:
  A given process will eventually enter the critical section

for parallel processes: *liveness is affected by the scheduling strategies.*

[4] In the first version of the slides of lecture 1, termination was defined misleadingly.

- *enabled* command in a state = statement can in principle be executed next
- concurrent programs: often more than 1 statement enabled.

Scheduling: resolving non-determinism

strategy such that for all points in an execution: if there is more than one statement enabled, pick one of them.

Fairness

Informally: enabled statements should not systematically be neglected by the scheduling strategy.

```
bool x := true;

co  while (x){}; || x := false co
```

- fairness: how to pick among enabled actions without being "passed over" indefinitely
- which are the potentially non-enabled actions in our language[5]
- note: possible status changes:
  - disabled → enabled (of course),
  - but also enabled → disabled
- Differently "powerful" forms of fairness: guarantee of progress for
  1. for actions that are always, out of principle, enabled
  2. for those that *stay enabled*
  3. for those whose enabledness show "on-off" behavior

---

[5] provided the control-flow/program pointer stands in front of them.

A scheduling strategy is *unconditionally fair* if each unconditional atomic action which can be chosen will eventually be chosen.

Example:

```
bool x := true;

co while (x){}; || x := false co
```

A scheduling strategy is *unconditionally fair* if each unconditional atomic action which can be chosen will eventually be chosen.

Example:

```
bool x := true;

co  while (x){}; || x := false co
```

- `x := false` is unconditional

⇒ will eventually be chosen

- This guarantees termination
- Example: "Round robin" execution
- note: if-then-else, **while** (b) ; are *not* conditional atomic statements!

Weak fairness

A scheduling strategy is *weakly fair* if

- it is unconditionally fair
- every conditional atomic action will eventually be chosen, assuming that the condition becomes true and thereafter remains true until the action is executed.

Example:

```
bool x = true, int y = 0;

co while (x) y = y + 1; || < await y >= 10; > x = false; o
```

Weak fairness

A scheduling strategy is *weakly fair* if

- it is unconditionally fair
- every conditional atomic action will eventually be chosen, assuming that the condition becomes true and thereafter remains true until the action is executed.

Example:

```
bool x = true, int y = 0;

co while (x) y = y + 1; || < await y >= 10; > x = false; o
```

- When `y >= 10` becomes true, this condition remains true
- This ensures termination of the program
- Example: Round robin execution

Strong fairness

Example

```
bool := true; y := false;

co
    while (x) y:=true; y:=false}
||
    < await(y) y:=false >
oc
```

Example

```
bool := true; y := false;

co
    while (x) y:=true; y:=false}
||
   < await(y) y:=false >
oc
```

Definition (Strongly fair scheduling strategy)

- unconditionally fair and
- each conditional atomic action will eventually be chosen, if the condition is true infinitely often.

Example

```
bool := true; y := false;

co
    while (x) y:=true; y:=false}
||
    < await(y) y:=false >
oc
```

Definition (Strongly fair scheduling strategy)

- unconditionally fair and
- each conditional atomic action will eventually be chosen, if the condition is true infinitely often.

for the example:

- under strong fairness: y true ∞-often $\Rightarrow$ termination
- under *weak fairness:* non-termination possible

Fairness for critical sections using locks

The CS solutions shown need to assume strong fairness to guarantee liveness, i.e., access for a given process (*i*):

- Steady inflow of processes which want the lock
- value of `lock` alternates (infinitely long) between `true` and `false`
- Weak fairness: Process *i* can read `lock` only when the value is `false`
- Strong fairness: Guarantees that *i* eventually sees that `lock` is `true`

Difficult: to make a scheduling strategy that is both practical and strongly fair.
We look at CS solutions where access is guaranteed for *weakly* fair strategies:

Fair solutions to the CS problem

- *Tie-Breaker*
- *Ticket*
- The book also describes the *bakery* algorithm

Tie-Breaker algorithm

- Requires no special machine instruction (like `TS`)
- We will look at the solution for two processes
- Each process has a private lock
- Each process sets its lock in the entry protocol
- The private lock is read, but is not changed by the other process

Naive solution

```
int in = 1          # possible values in {1,2}

process p1 {                      process p2 {
  while (true) {                    while (true) {
    while (in=2) {skip};              while (in=1) {skip};
    CS;                               CS;
    in := 2;                          in := 1
    non-CS                            non-CS
  }
```

- entry-protocol: active/busy waiting
- exit protocol: atomic assignment

Good solution? A solution at all? What's good, what's less so?

Tie-Breaker algorithm: Attempt 1

```
in1 := false, in2 := false;

process p1 {
  while (true){
    while (in2) {skip};
    in1 := true;
     CS
    in1 := false;
     non-CS
  }
}
```

```
process p2 {
  while (true) {
  while (in1) {skip};
    in2 := true;
      CS  ;
    in2 := false;
      non-CS
  }
}
```

Tie-Breaker algorithm: Attempt 1

```
in1 := false , in2 := false ;

process p1 {
  while (true){
   while (in2) {skip};
   in1 := true;
    CS
   in1 := false;
    non-CS
  }
}

process p2 {
  while (true) {
  while (in1) {skip};
    in2 := true;
       CS ;
    in2 := false;
       non-CS
  }
}
```

No *mutex*

Tie-Breaker algorithm: Attempt 2

- problem seems entry protocol
- reverse the order: first "set", then "test"

```
in1 := false , in2 := false ;

process p1 {
  while (true){
    in1 := true;
    while (in2) {skip};
     CS
     in1 := false;
     non−CS
  }
}

process p2 {
  while (true) {
    in2 := true;
    while (in1) {skip};
       CS ;
       in2 := false;
       non−CS
  }
}
```

Tie-Breaker algorithm: Attempt 2

- problem seems entry protocol
- reverse the order: first "set", then "test"

```
in1 := false , in2 := false ;
```

```
process p1 {
  while (true){
   in1 := true;
   while (in2) {skip};
    CS
    in1 := false;
    non—CS
  }
}
```

```
process p2 {
  while (true) {
   in2 := true;
   while (in1) {skip};
    CS ;
    in2 := false;
    non—CS
  }
}
```

Deadlock[6] *: - (*

[6] Technically, it's more of a live-lock, since the processes still are doing "something", namely spinning endlessly in the empty while-loops, never leaving the entry-protocol to do real work. The situation though is analogous to a "deadlock" conceptually.

Tie-Breaker algorithm: Attempt 3 (with await)

- problem: both half flagged their wish to enter ⇒ deadlock
- avoid deadlock: “tie-break”
- be fair: not always give priority to one specific process
- which tells which process last started the entry protocol.
- add variable `last`

Tie-Breaker algorithm: Attempt 3 (with await)

- problem: both half flagged their wish to enter ⇒ deadlock
- avoid deadlock: "tie-break"
- be fair: not always give priority to one specific process
- which tells which process last started the entry protocol.
- add variable `last`

```
in1 := false, in2 := false; int last
```

```
process p1 {
  while (true){
    in1 := true;
    last := 1;
    < await ( (not in2) or
              last = 2);>
    CS
    in1 := false;
    non−CS
  }
}
```

```
process p2 {
  while (true){
    in2 := true;
    last := 2;
    < await ( (not in1) or
              last = 1);>
    CS
    in2 := false;
    non−CS
  }
}
```

Even if the variables `in1`, `in2` and `last` can change the value while a wait condition evaluates to true,
the wait condition will *remain true*.
`p1` sees that the wait condition is true:

- `in2 == false`
  - `in2` can eventually become `true`, but then `p2` must also set `last` to 2
  - Then the await condition to `p1` still holds
- `last == 2`
  - Then `last == 2` will hold until `p1` has executed

Thus we can replace the **await**-statement with a **while**-loop.

Tie-Breaker algorithm (4)

```
process p1 {
  while (true){
    in1 := true;
    last := 1;
    while  (in2 and last = 2){skip}
    CS
    in1 := false;
    non-CS
  }
}
```

generalizable to many processes (see book)

If the Tie-Breaker algorithm is scaled up to n processes, we get a loop with $n - 1$ 2-process Tie-Breaker algorithms.
The ticket algorithm provides a simpler solution to the CS problem for n processes.

- Works like the "take a number" queue at the post office (with one loop)
- A customer (process) which comes in takes a number which is higher than the number of all others who are waiting
- The customer is served when a ticket window is available and the customer has the lowest ticket number.

Ticket algorithm: Sketch (*n* processes)

```
int number := 1; next := 1; turn[1:n] := ([n] 0);

process [i = 1 to n] {
  while (true) {
    < turn[i] := number; number := number +1 >;
    < await (turn[i] = next)>;
    CS
    <next = next + 1>;
    non-CS
  }
}
```

- The first line in the loop must be performed atomically!
- **await**-statement: can be implemented as while-loop
- Some machines have an *instruction*

Fetch-and-add

```
FA(var, incr):<int tmp := var; var := var + incr; return tmp;>
```

Ticket algorithm: Implementation

```
int number := 1; next := 1; turn[1:n] := ([n] 0);

process [i = 1 to n] {
  while (true) {
    turn[i] := FA(number, 1);
    while (turn [i] != next) {skip};
    CS
    next := next + 1;
    non-CS
  }
}
```

`FA(var, incr):<int tmp = var; var = var + incr; return tmp`

Without this instruction, we use an extra CS:[7]

`CSentry; turn[i]=number; number = number + 1; CSexit;`

Problem with *fairness* for CS. Solved with the *bakery algorithm* (see book).

[7] ?! isn't that a bit strange?

Ticket algorithm: Invariant

Invariants

- *global* invariant

$$0 < next \leq number$$

- For proc. i:
  - `turn[i] < number`
  - if `p[i]` is in the CS then `turn[i] == next`.
- for pairs of processes $i \neq j$:

if `turn[i] > 0` *then* `turn[j]` $\neq$ `turn[i]`

This holds initially, and is preserved by all atomic statements.

- Computation of disjoint parts in parallel (e.g. array elements).
- Processes go into a loop where each iteration is dependent on the results of the previous.

```
process Worker[i=1 to n] {
  while (true) {
    task i;
     wait until all n tasks are done      # barrier
  }
}
```

All processes must reach the barrier ("join") before any can continue.

A number of processes will synchronize the end of their tasks. Synchronization can be implemented with a *shared counter*:

```
int count := 0;}
process Worker[i=1 to n] {
 while (true) {
   task i;
   < count := count+1>;
   < await(count=n)>;
 }
}
```

Can be implemented using the FA instruction.
Disadvantages:

- count must be reset between each iteration.
- Must be updated using atomic operations.
- Inefficient: Many processes read and write count concurrently.

Goal: Avoid too much read- and write-operations on one variable.
Divides shared counter into several local variables.

```
Worker[i]:
          arrive[i] = 1;
          < await (continue[i] == 1);>
Coordinator:
          for [i=1 to n] < await (arrive[i]==1);>
          for [i=1 to n] continue[i] = 1;
```

In a loop, the flags must be cleared before the next iteration.
Flag synchronization principles:

1. The process which waits for a flag is the one which will reset the flag
2. A flag will not be set before it is reset

both arrays initialized to 0.

```
process Worker [i = 1 to n] {
  while (true) {
    code to implement task i;
    arrive[i] := 1;
    < await (continue[i] := 1>;
    continue := 0;
  }
}
```

```
process Coordinator {
  while (true) {
    for [i = 1 to n] {
      <await (arrived[i] = 1)>;
      arrived[i] := 0
      };
    for [i = 1 to n] {
      continue[i] := 1
    }
  }
}
```

Combined barriers

- The roles of the Worker and Coordinator processes can be *combined*.
- In a *combining tree barrier* the processes are organized in a tree structure. The processes signal *arrive* upwards in the tree and *continue* downwards in the tree.

Implementation of Critical Sections

```
        bool lock = false;
Entry:  <await (!lock) lock = true>
        Critical section
Exit:   <lock = false;>
```

Spin lock implementation of entry: `while (TS(lock)) skip`

Drawbacks:

- Busy waiting protocols are often complicated
- Inefficient if there are fever processors than processes
  - Should not waste time executing a skip loop
- No clear distinction between variables used for synchronization and computation

Desirable to have a special tools for synchronization protocols: semaphores (next lecture)

[1] G. R. Andrews.

Foundations of Multithreaded, Parallel, and Distributed Programming.

Addison-Wesley, 2000.

[2] E. W. Dijkstra.

Solution of a problem in concurrent programming control.

Communications of the ACM, 8(9):569, 1965.