# Lesson: An introduction to Fork

Programming model
Hello World
Shared and private variables
Expression-level synchronous execution
Multiprefix operators
Synchronicity declaration
Synchronous regions: Group concept
Asynchronous regions: Critical sections and locks
Sequential vs. synchronous parallel critical sections
`join` statement
Software packages for Fork

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# The PRAM programming language Fork

language design: [Hagerup/Seidl/Schmitt'89] [K./Seidl'95,'97] [Keller,K.,Träff'00]

**extension of C**

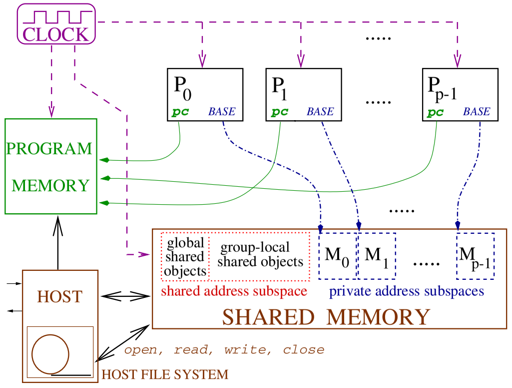
**Arbitrary CRCW PRAM with atomic multiprefix operators**

**synchronicity of the PRAM transparent at expression level**

**variables to be declared either private or shared**

**private address subspaces embedded in shared memory**

**implementation for SB-PRAM**



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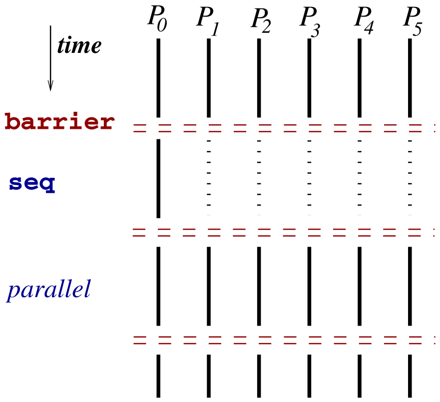
# SPMD style of parallel program execution

- fixed set of processors

- no spawn() command

- main() executed by all started processors as one group



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# Hello World

```
#include <fork.h>
#include <io.h>

void main( void )
{
 if (__PROC_NR__ == 0)
   printf("Program executed by\
          %d processors\n",
           __STARTED_PROCS__ );
 barrier;
 pprintf("Hello world from P%d\n",
           __PROC_NR__ );
}
```

```
PRAM P0 = (p0, v0)> g
Program executed by 4 processors

#0000# Hello world from P0
#0001# Hello world from P1
#0002# Hello world from P2
#0003# Hello world from P3
EXIT: vp=#0, pc=$000001fc
EXIT: vp=#1, pc=$000001fc
EXIT: vp=#2, pc=$000001fc
EXIT: vp=#3, pc=$000001fc
Stop nach 11242 Runden, 642.400 kIps
01fc 18137FFF   POPNG   R6, ffffffff, R
PRAM P0 = (p0, v0)>
```

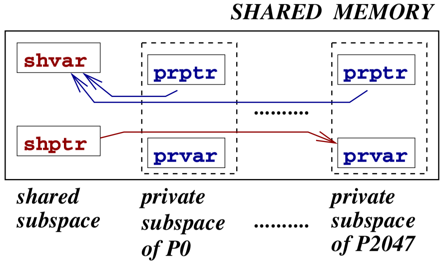
## Shared and private variables

- each variable is classified as either shared or private "sharity"
- sh relates to defining group of processors
- pointers: no specification of pointee's sharity required

```
pr int prvar, *prptr;
sh int shvar, *shptr;

prptr = &shvar;

shptr = &prvar;  // concurrent write!
```



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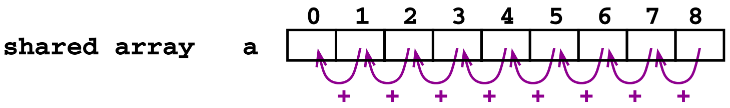
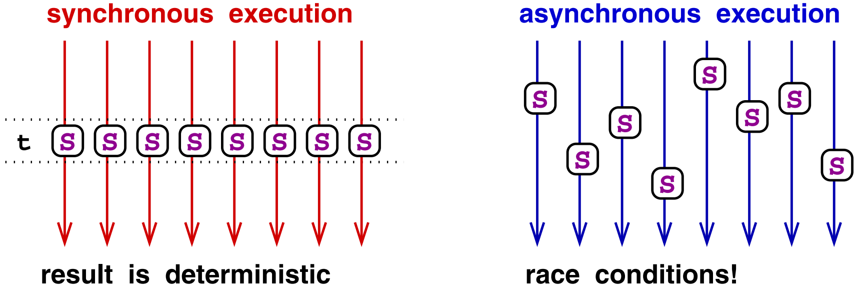
## Synchronous execution at the expression level



```
S:   a[$$] = a[$$] + a[$$+1];

                    //  $$ in {0..p-1} is processor rank
```



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## Expressions: Atomic Multiprefix Operators (for integers only)

Set $P$ of processors executes simultaneously

$$k \ = \ \mathtt{mpadd}(\ ps,\ \ expression\ \ );$$

Let $ps_i$ be the location pointed to by the $ps$ expression of processor $i \in P$.
Let $s_i$ be the old contents of $ps_i$.
Let $Q_{ps} \subseteq P$ denote the set of processors $i$ with $ps_i = ps$.
Each processor $i \in P$ evaluates $expression$ to a value $e_i$.

Then the result returned by `mpadd` to processor $i \in P$ is the prefix sum

$$k \leftarrow s_i + \sum_{j \in Q_{s_i},\ j<i} e_j$$

and memory location $ps_i$ is assigned the sum

$$*ps_i \leftarrow s_i + \sum_{j \in Q_{s_i}} e_j$$

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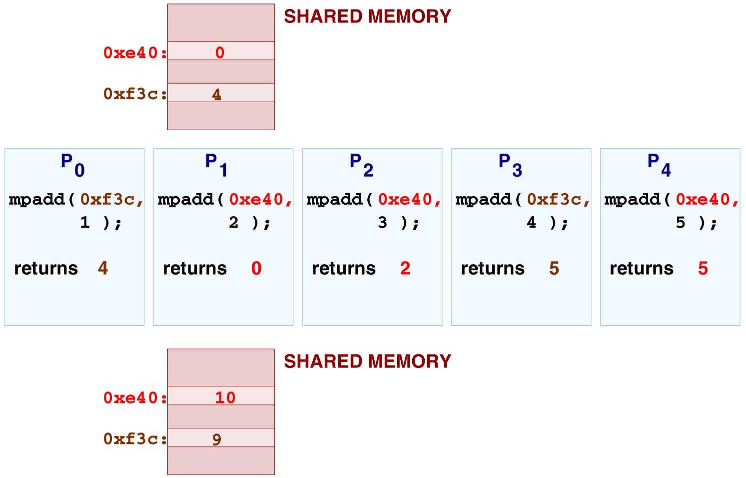
## Example: Multiprefix addition



| $P_0$ | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| `mpadd( 0xf3c, 1 );` | `mpadd( 0xe40, 2 );` | `mpadd( 0xe40, 3 );` | `mpadd( 0xf3c, 4 );` | `mpadd( 0xe40, 5 );` |
| returns 4 | returns 0 | returns 2 | returns 5 | returns 5 |

`mpadd` may be used as atomic *fetch&add* operator.

## Expressions: Atomic Multiprefix Operators (cont.)

### Example: User-defined consecutive numbering of processors

```
sh int counter = 0;
pr int me = mpadd( &counter, 1 );
```

### Similarly:

`mpmax` (multiprefix maximum)
`mpand` (multiprefix bitwise and)
`mpand` (multiprefix bitwise or)

`mpmax` may be used as atomic *test&set* operator.

### Example:

```
  pr int oldval = mpmax( &shmloc, 1 );
```

---

## Atomic Update Operators / ilog2

`syncadd(`$ps$`, `$e$`)` atomically add value $e$ to contents of location $ps$
`syncmax` atomically update with maximum
`syncand` atomically update with bitwise and
`syncor` atomically update with bitwise or

`ilog2(`$k$`)` returns $\lfloor \log_2 k \rfloor$ for integer $k$

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## Synchronous and asynchronous program regions

```
sync int *sort( sh int *a, sh int n )
{ extern straight int compute_rank( int *, int);
  if ( n>0 ) {
     pr int myrank = compute_rank( a, n );
     a[myrank] = a[__PROC_NR__];
     return a;
  }
  else
     farm  {
        printf("Error: n=%d\n", n);
        return NULL;
     }
}
extern async int *read_array( int * );
extern async int *print_array( int *, int );
sh int *A, n;
async void main( void )
{
  A = read_array( &n );
  start {
     A = sort( A, n );
     seq  if (n<100) print_array( A, n );
  }
}
```

Fork program code regions statically classified as either synchronous, straight, or asynchronous.

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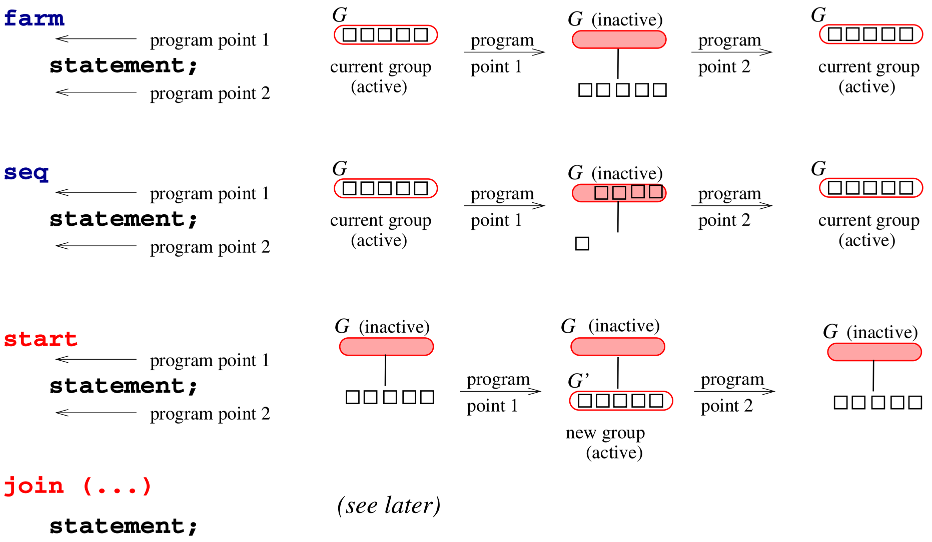
## Switching from synchronous to asynchronous mode and vice versa



**farm**
**statement;**

**seq**
**statement;**

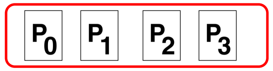
**start**
**statement;**

**join (...)**
**statement;**

*(see later)*

## Group concept

Groups of processors are explicit:



**Group ID: @**
**Group size: # or `groupsize()`**
**Group rank: $$ (automatically ranked from 0 to #-1)**

+ Scope of sharing for function-local variables and formal parameters
+ Scope of barrier-synchronization
+ Scope of synchronous execution

Synchronicity invariant: (in synchronous regions):
All processors in the same active group operate synchronously.

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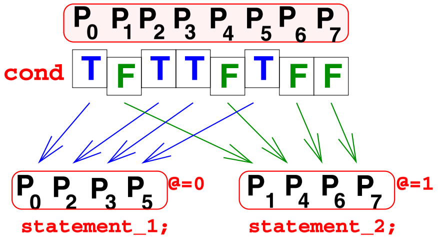
## Implicit group splitting: IF statement with private condition

```
if (cond)
        statement_1;
else
        statement_2;
```




private condition expression

→ current group $G$ of processors must be split into 2 subgroups to maintain synchronicity invariant.

(parent) group $G$ is reactivated after subgroups have terminated

→ $G$-wide barrier synchronization

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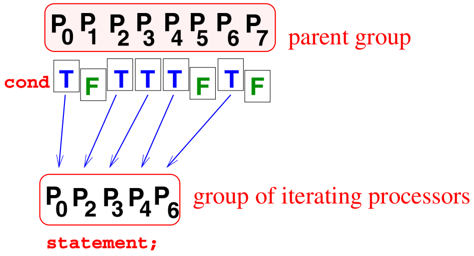
## Implicit subgroup creation: Loop with private condition

```
while ( cond ) do

        statement;
```

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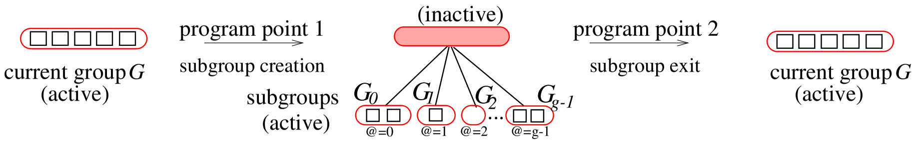
## Explicit group splitting: The `fork` statement

```
fork ( g; @ = fn($$); $=$$)
      statement;
```

← program point 1

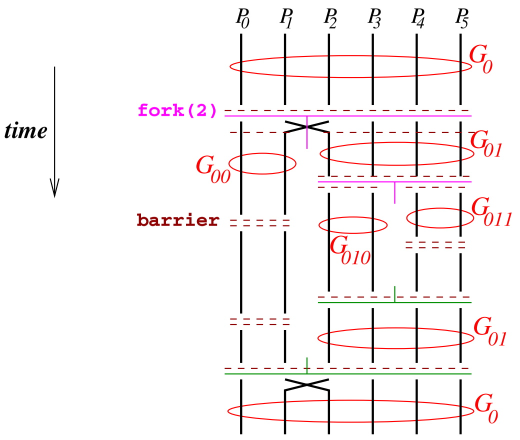
← program point 2

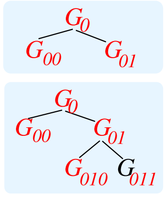


body statement is executed in parallel by all subgroups in parallel

(parent) group $G$ is reactivated when all subgroups have terminated and resumes after $G$-wide barrier synchronization at program point 2

# The group hierarchy tree





**Group hierarchy tree**

Dynamic / recursive splitting of groups into disjoint subgroups

→ at any time the group hierarchy is a logical tree.

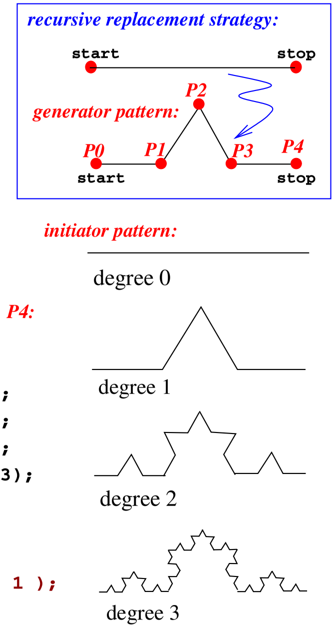
supports nested (multi-level) parallelism

# Example: Drawing Koch curves in parallel (1)

## Sequential algorithm:

```
void seq_Koch ( int startx, int starty,
                int stopx, int stopy, int level )
{
 int x[5], y[5], dx, dy;
 int i;
 if (level >= DEGREE) {   // reach limit of recursion:
    seq_line( startx, starty,
              stopx, stopy, color, width );
    return;
 }
 // compute x and y coordinates of interpolation points  P0, P1, P2, P3, P4:
 dx = stopx - startx;        dy = stopy - starty;
 x[0] = startx;              y[0] = starty;
 x[1] = startx + (dx/3);     y[1] = starty + (dy/3);
 x[2] = startx + dx/2 - (int)(factor * (float)dy);
 y[2] = starty + dy/2 + (int)(factor * (float)dx);
 x[3] = startx + (2*dx/3); y[3] = starty + (2*dy/3);
 x[4] = stopx;               y[4] = stopy;

 for ( i=0; i<4; i++ )    // 4 recursive calls
    seq_Koch( x[i], y[i], x[i+1], y[i+1], level + 1 );
}
```



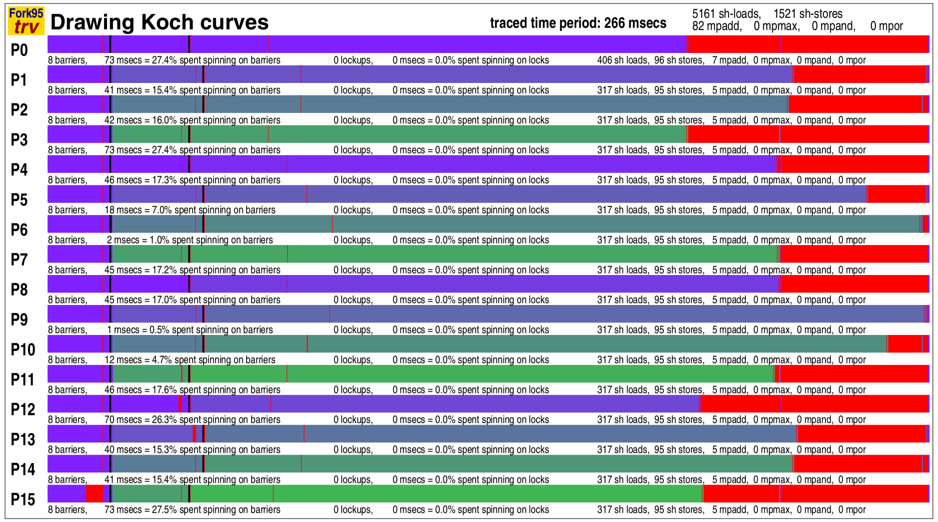
# Example: Drawing Koch curves in parallel (2)

```
sync void Koch ( sh int startx, sh int starty,
                 sh int stopx,  sh int stopy,  sh int level )
{
 sh int x[5], y[5], dx, dy;
 pr int i;

 if (level >= DEGREE) {   // terminate recursion:
    line( startx, starty, stopx, stopy, color, width );
    return;
 }
 seq {    // linear interpolation:
    dx = stopx - startx;       dy = stopy - starty;
    x[0] = startx;             y[0] = starty;
    x[1] = startx + (dx/3);    y[1] = starty + (dy/3);
    x[2] = startx + dx/2 - (int)(factor * (float)dy);
    y[2] = starty + dy/2 + (int)(factor * (float)dx);
    x[3] = startx + (2*dx/3); y[3] = starty + (2*dy/3);
    x[4] = stopx;              y[4] = stopy;
 }
 if (# < 4)    // not enough processors in the group?
    for ( i=$$; i<4; i+=# )      // partially parallel divide-and-conquer step
       farm seq_Koch( x[i], y[i], x[i+1], y[i+1], level + 1 );
 else
    fork ( 4; @ = $$ % 4; )      // parallel divide-and-conquer step
       Koch( x[@], y[@], x[@+1], y[@+1], level + 1 );
}
```

# Program trace visualization with the trv tool

**-T: instrument the target code to write events to a trace file. Can be processed with trv to FIG image**



```
Drawing Koch curves          traced time period: 266 msecs   5161 sh-loads,   1521 sh-stores
                                                             82 mpadd,  0 mpmax,  0 mpand,  0 mpor
P0
8 barriers,  73 msecs = 27.4% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   406 sh loads,  96 sh stores,  7 mpadd,  0 mpmax,  0 mpand,  0 mpor
P1
8 barriers,  41 msecs = 15.4% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P2
8 barriers,  42 msecs = 16.0% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P3
8 barriers,  73 msecs = 27.4% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P4
8 barriers,  46 msecs = 17.3% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P5
8 barriers,  18 msecs = 7.0% spent spinning on barriers    0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P6
8 barriers,   2 msecs = 1.0% spent spinning on barriers    0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P7
8 barriers,  45 msecs = 17.2% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P8
8 barriers,  45 msecs = 17.0% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P9
8 barriers,   1 msecs = 0.5% spent spinning on barriers    0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P10
8 barriers,  12 msecs = 4.7% spent spinning on barriers    0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P11
8 barriers,  46 msecs = 17.6% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P12
8 barriers,  70 msecs = 26.3% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P13
8 barriers,  40 msecs = 15.3% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P14
8 barriers,  41 msecs = 15.4% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
P15
8 barriers,  73 msecs = 27.5% spent spinning on barriers   0 lockups,  0 msecs = 0.0% spent spinning on locks   317 sh loads,  95 sh stores,  5 mpadd,  0 mpmax,  0 mpand,  0 mpor
```

# Asynchronous regions: Critical sections and locks (1)

**Asynchronous concurrent read + write access to shared data objects constitutes a critical section**

**(danger of race conditions, visibility of inconsistent states, nondeterminism)**

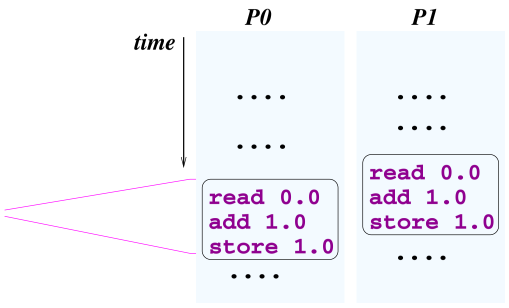
**Example:**

```
sh float var = 0.0;

....
farm {
   ....

   var = var + 1.0;

   ....
}
```



**Access to var must be atomic.**

**Atomic execution can be achieved by sequentialization (mutual exclusion).**

---

# Asynchronous regions: Critical sections and locks (2)

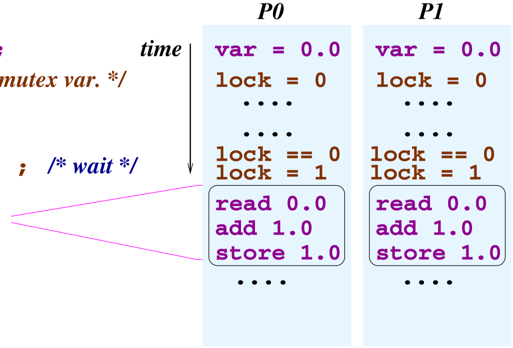
**Asynchronous concurrent read + write access to shared data objects constitutes a critical section**

**(danger of race conditions, visibility of inconsistent states, nondeterminism)**

**Example:**

```
sh float var = 0.0;
sh int lock = 0; /* mutex var. */
....
farm {
   ....
   while (lock > 0) ;  /* wait */
   lock = 1;
   var = var + 1.0;
   lock = 0;
   ....
}
```

!!NOT ATOMIC!!



**Access to var must be atomic.**

**Atomic execution can be achieved by sequentialization (mutual exclusion).**

**Access to the lock variable must be atomic as well: fetch&add or test&set**

---

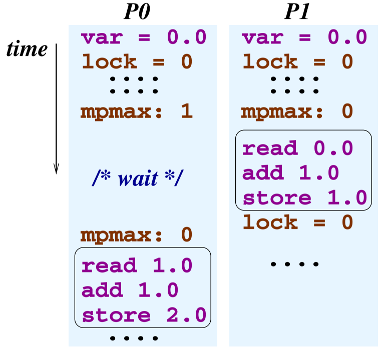
# Asynchronous regions: Critical sections and locks (3)

**Asynchronous concurrent read + write access to shared data objects constitutes a critical section**

**(danger of race conditions, visibility of inconsistent states, nondeterminism)**

**Example:**

```
sh float var = 0.0;
sh int lock = 0;
....
farm {
   ....
   while (mpmax(&lock, 1)) ;
                          /* wait */
   var = var + 1.0;
   lock = 0;
   ....
}
```



**Access to var must be atomic.**

**Atomic execution can be achieved by sequentialization (mutual exclusion).**

**Access to the lock variable must be atomic as well: fetch&add or test&set**

**in Fork: use the mpadd / mpmax / mpand / mpor operators**

---

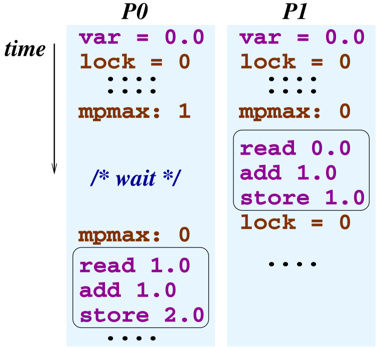
# Asynchronous regions: Critical sections and locks (4)

**Asynchronous concurrent read + write access to shared data objects constitutes a critical section**

**(danger of race conditions, visibility of inconsistent states, nondeterminism)**

**Example:**

```
sh float var = 0.0;
sh SimpleLock sl;
seq sl = new_SimpleLock();
....
farm {
   ....
   simple_lockup( sl );
                          /* wait */
   var = var + 1.0;
   simple_unlock( sl );
   ....
}
```



**Access to var must be atomic.**

**Atomic execution can be achieved by sequentialization (mutual exclusion).**

**Access to the lock variable must be atomic as well: fetch&add or test&set**

**in Fork: alternatively: use predefined lock data types and routines**

# Asynchronous regions: Predefined lock data types and routines

**(a) Simple lock**

```
SimpleLock new_SimpleLock ( void );
void simple_lock_init ( SimpleLock s );
void simple_lockup ( SimpleLock s );
void simple_unlock ( SimpleLock s );
```

**(b) Fair lock** (FIFO order of access guaranteed)

```
FairLock new_FairLock ( void );
void fair_lock_init ( FairLock f );
void fair_lockup ( FairLock f );
void fair_unlock ( FairLock f );
```

**(c) Readers/Writers lock** (multiple readers OR single writer)

```
RWLock new_RWLock ( void );
void rw_lock_init ( RWLock r );
void rw_lockup ( RWLock r, int mode );
void rw_unlock ( RWLock r, int mode, int wait );
                      mode in { RW_READ, RW_WRITE }
```

**(d) Readers/Writers/Deletors lock** (lockup fails if lock is being deleted)

```
RWDLock new_RWDLock ( void );
void rwd_lock_init ( RWDLock d );
int  rwd_lockup ( RWDLock d, int mode );
void rwd_unlock ( RWDLock d, int mode, int wait );
                      mode in { RW_READ, RW_WRITE, RW_DELETE }
```

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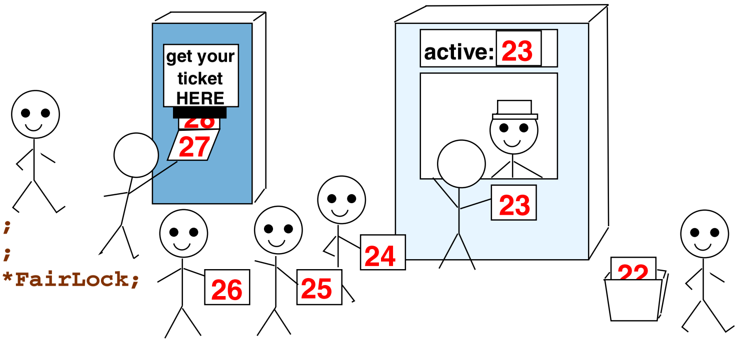
# Asynchronous regions: Implementation of the fair lock

**2 counters:**

```
struct {
   int ticket;
   int active;
} fair_lock, *FairLock;
```



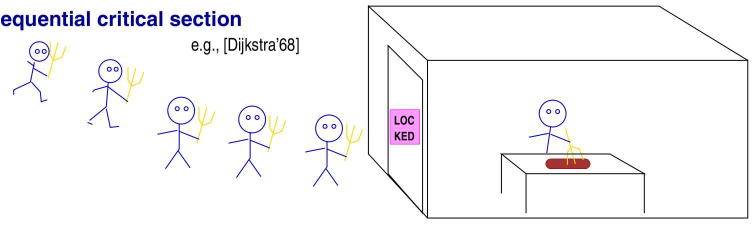
```
void fair_lockup ( FairLock fl )
{
  int myticket = mpadd( &(fl->ticket), 1);/*atomic fetch&add*/
  while (myticket > fl->active) ;    /*wait*/
}

void fair_unlock ( FairLock fl )
{
  syncadd( &(fl->active), 1 ); /*atomic increment*/
}
```

---

# Sequential vs. synchronous parallel critical sections (1)

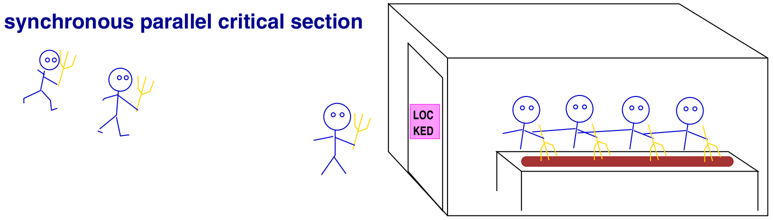
**sequential critical section**

e.g., [Dijkstra'68]



-> sequentialization of concurrent accesses to a shared object / resource

**synchronous parallel critical section**



-> allow simultaneous entry of more than one processor
-> deterministic parallel access by executing a synchronous parallel algorithm
-> at most one group of processors inside at any point of time

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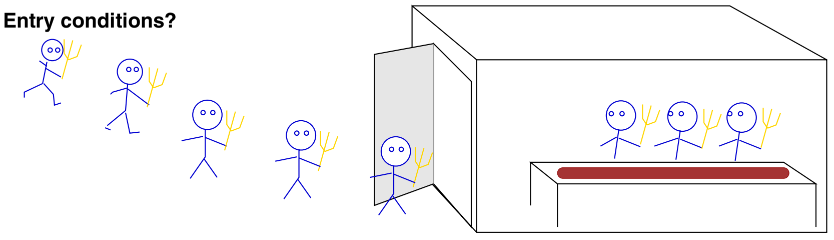
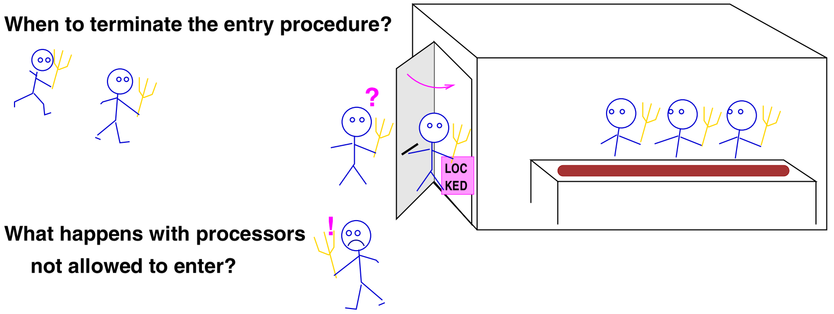
# Sequential vs. synchronous parallel critical sections (2)

**Entry conditions?**



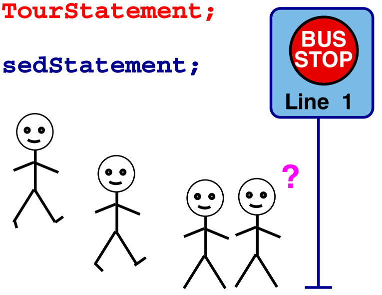
**When to terminate the entry procedure?**



**What happens with processors not allowed to enter?**

# The join statement: excursion bus analogy (1)

```
join  ( SMsize; delayCond; stayInsideCond )
      busTourStatement;
else
      missedStatement;
```

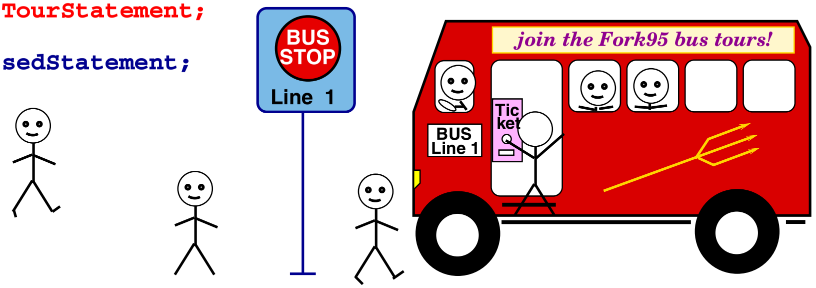


**Bus gone?**
- execute else part: `missedStatement;`
- continue in else part: jump back to bus stop (join entry point)
- break in else part: continue with next activity (join exit point)

---

# The join statement: excursion bus analogy (2)

```
join  ( SMsize; delayCond; stayInsideCond )
      busTourStatement;
else
      missedStatement;
```

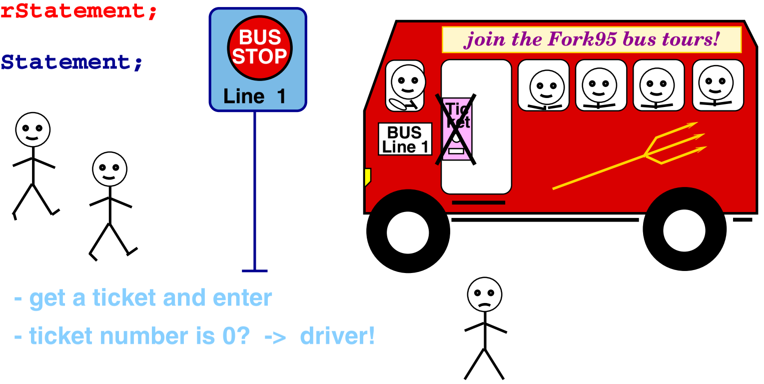


**Bus waiting:**
- get a ticket and enter
- ticket number is 0? -> driver!
  driver initializes shared memory (SMsize) for the bus group
  driver then waits for some event: `delayCond`
  driver then switches off the ticket automaton

---

# The join statement: excursion bus analogy (3)

```
join  ( SMsize; delayCond; stayInsideCond )
      busTourStatement;
else
      missedStatement;
```

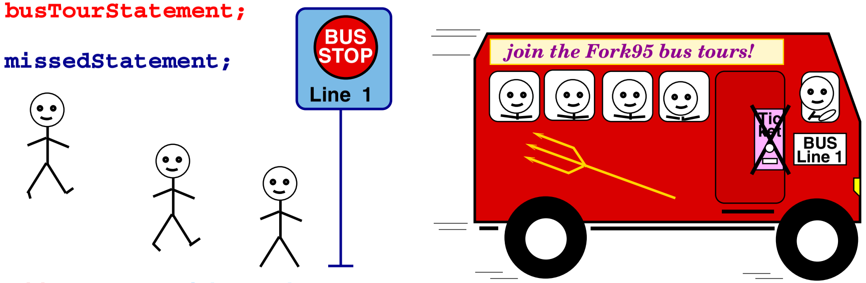


**Bus waiting:**
- get a ticket and enter
- ticket number is 0? -> driver!
- if not `stayInsideCond` spring off and continue with else part

---

# The join statement: excursion bus analogy (4)

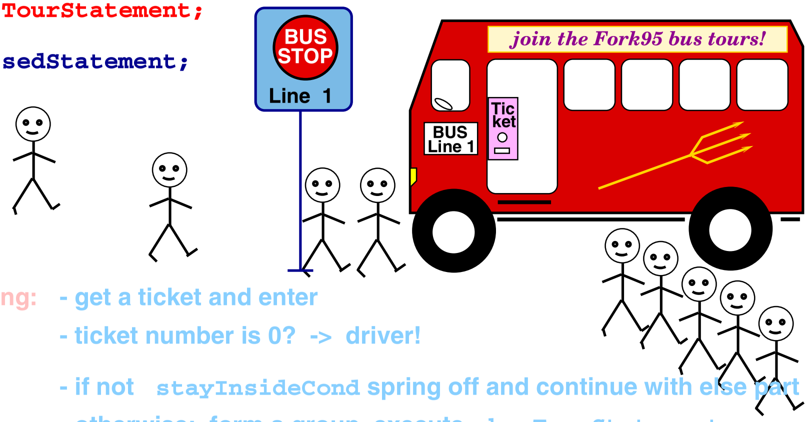
```
join  ( SMsize; delayCond; stayInsideCond )
      busTourStatement;
else
      missedStatement;
```



**Bus waiting:**
- get a ticket and enter
- ticket number is 0? -> driver!
- if not `stayInsideCond` spring off and continue with else part
- otherwise: form a group, execute `busTourStatement` synchronously

## The join statement: excursion bus analogy (5)

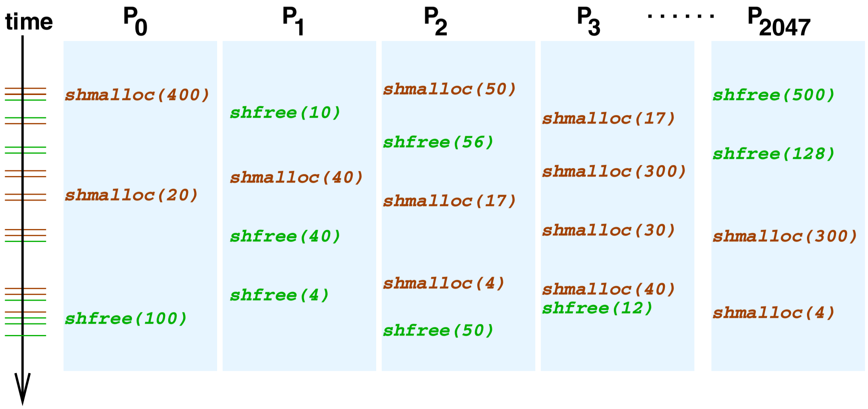
```
join ( SMsize; delayCond; stayInsideCond )
     busTourStatement;
else
     missedStatement;
```



**Bus waiting:** - get a ticket and enter
- ticket number is 0? -> driver!
- if not `stayInsideCond` spring off and continue with else part
- otherwise: form a group, execute `busTourStatement`
- at return: leave the bus, re-open ticket automaton and continue with next activity

---

## The join statement, example (1): parallel shared heap memory allocation



| $P_0$ | $P_1$ | $P_2$ | $P_3$ | $P_{2047}$ |
|---|---|---|---|---|
| shmalloc(400) | shfree(10) | shmalloc(50) | shmalloc(17) | shfree(500) |
| shmalloc(20) | shmalloc(40) | shfree(56) | shmalloc(300) | shfree(128) |
| shfree(100) | shfree(40) | shmalloc(17) | shmalloc(30) | shmalloc(300) |
| | shfree(4) | shmalloc(4) | shmalloc(40) | shmalloc(4) |
| | | shfree(50) | shfree(12) | |

**Idea:** - use a synchronous parallel algorithm for shared heap administration
- collect multiple queries to shmalloc() / shfree() with join() and process them as a whole in parallel!

**Question:** Does this really pay off in practice?

---

## The join statement, example (2)

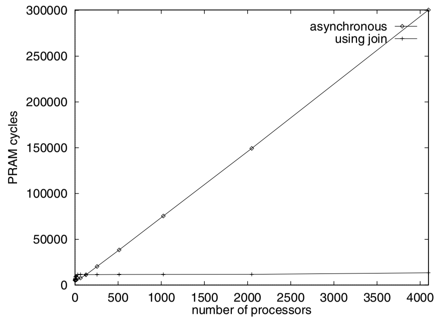
Experiment:

Simple block–oriented parallel shared heap memory allocator

First variant: sequential critical section, using a simple lock

Second variant: parallel critical section, using `join`

| $p$ | asynchronous | | using `join` | |
|---|---|---|---|---|
| 1 | 5390 cc | (21 ms) | 6608 cc | (25 ms) |
| 2 | 5390 cc | (21 ms) | 7076 cc | (27 ms) |
| 4 | 5420 cc | (21 ms) | 8764 cc | (34 ms) |
| 8 | 5666 cc | (22 ms) | 9522 cc | (37 ms) |
| 16 | 5698 cc | (22 ms) | 10034 cc | (39 ms) |
| 32 | 7368 cc | (28 ms) | 11538 cc | (45 ms) |
| 64 | 7712 cc | (30 ms) | 11678 cc | (45 ms) |
| 128 | 11216 cc | (43 ms) | 11462 cc | (44 ms) |
| 256 | 20332 cc | (79 ms) | 11432 cc | (44 ms) |
| 512 | 38406 cc | (150 ms) | 11556 cc | (45 ms) |
| 1024 | 75410 cc | (294 ms) | 11636 cc | (45 ms) |
| 2048 | 149300 cc | (583 ms) | 11736 cc | (45 ms) |
| 4096 | 300500 cc | (1173 ms) | 13380 cc | (52 ms) |



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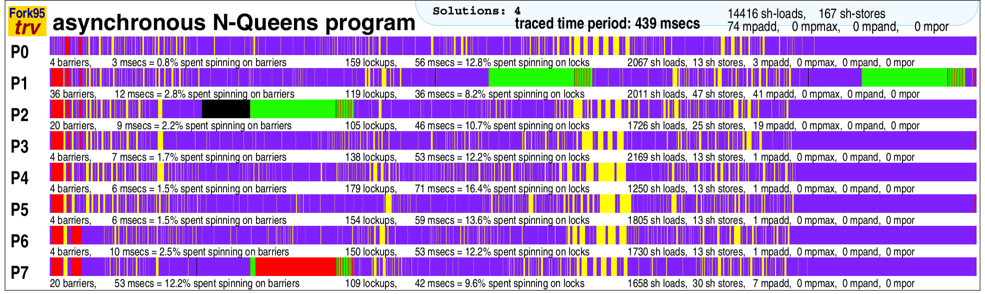
## The join statement, example (3)

asynchronous parallel
N-queens program uses
join for parallel output
of solutions

```
PRAM P0 = (p0, v0)> g
Enter N = 6
Computing solutions to the 6-Queens problem...
-------------------- Next 2 solutions (1..2): --------------------
|..Q...|...Q..
|.....Q|Q.....
|.Q....|....Q.
|....Q.|.Q....
|Q.....|.....Q
|...Q..|..Q...
-------------------- Next 1 solutions (3..3): --------------------
|.Q....
|...Q..
|.....Q
|Q.....
|..Q...
|....Q.
-------------------- Next 1 solutions (4..4): --------------------
|....Q.
|..Q...
|Q.....
|.....Q
|...Q..
|.Q....
Solutions: 4
```



# Available software packages

PAD library [Träff'95–98], [PPP 8]

PRAM algorithms and data structures

APPEND library [PPP 7.4]

asynchronous parallel data structures

MPI core implementation in Fork [PPP 7.6]

Skeleton functions [PPP 7]

generic map, reduce, prefix, divide-and-conquer, pipe, ...

FView fish-eye viewer for layouted graphs [PPP 9]

N-body simulation [PPP 7.8]