Compiling CSP

or having fun with a new occam-π compiler and CSP

(and fringe presentation)

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Contents

Motivation

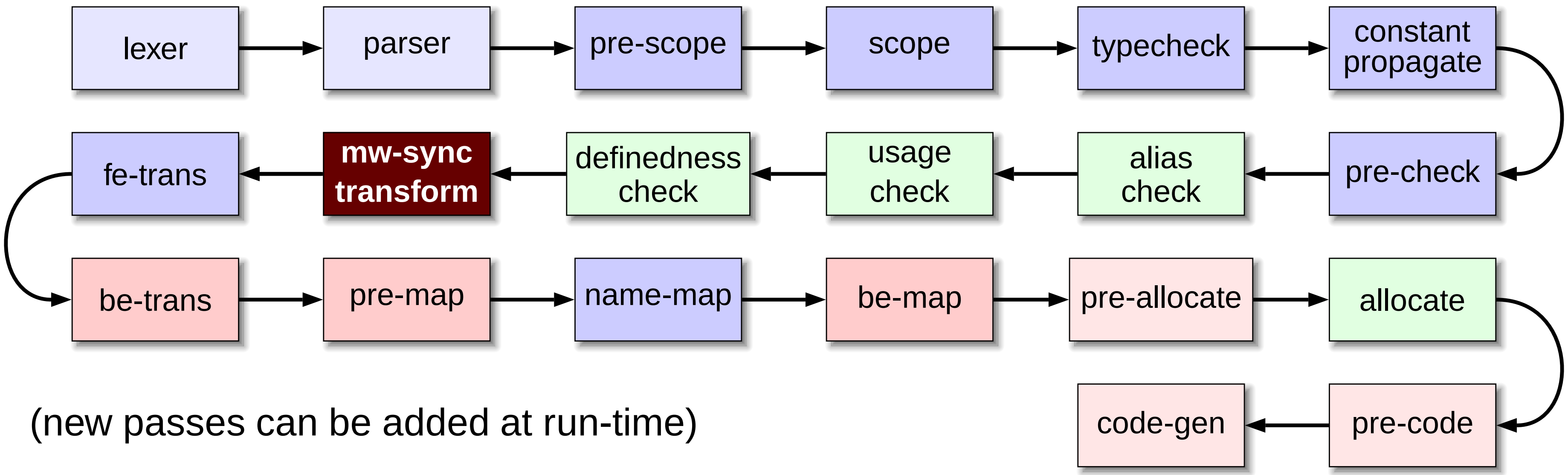
- **CSP**, Hoare's Communicating Sequential Processes, is a process algebra for describing **concurrent** processes and their interactions
  - CSP itself primarily used for **formal modelling**
  - e.g. with tools such as **FDR** and **ProBE**
- Can describe some interesting and complex systems with CSP
  - including some that we cannot yet implement directly
  - e.g. with tools such as **KRoC/occam-π**, **JCSP**, **C++CSP**, **CTJ**, etc.
- This work is concerned with the **compilation** of CSP to executable code
  - so that we can experiment with interesting and complex systems :-)
  - including the **TUNA** project's models of platelet behaviour (investigating models of blood-clotting and, more generally, **nanite assemblers**)

The New occam-π Compiler

- A new occam-π compiler to replace the existing compiler in KRoC
  - the existing compiler is becoming increasing difficult to maintain
  - based on a fairly old (but industry proven) code base, mostly 1987
  - designed to run in 2 MB of memory, so quite compact/optimal in places
  - but was never really designed to handle the dynamics introduced by occam-π
  - written in C, started off around 60,000 lines, now at around 120,000
- Currently around 55,000 lines of C code, named **NOCC**
  - maybe not the best language for implementing compilers ...
  - and do we really need another compiler ?
  - on the other hand, few compilers have low-level representations for parallelism (mostly in compilers for parallel hardware)

The New occam-π Compiler

- The CSP language implemented does not require a hugely complex compiler
  - good test of NOCC's ability to handle different source languages
  - NOCC already generates ETC (virtual transputer byte-code), translated to native code and linked with the existing KRoC/occam-π run-time
- An extensible monolithic multi-pass compiler:



(new passes can be added at run-time)

The New occam-π Compiler

- When it starts up, the compiler is ‘empty’
  - Parse tree structures and the parser built dynamically:

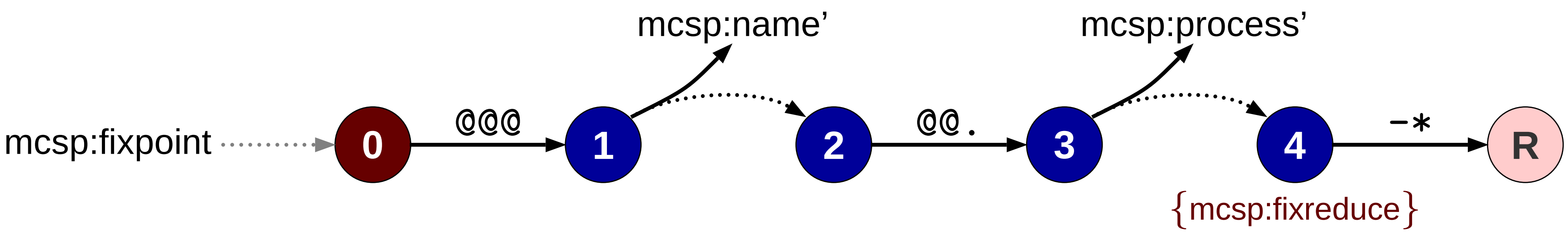
2 subnodes, 0 names, 0 hooks

```
tndef_t *tnd;  ntdef_t *tag;
tnd = tnode_newnodetype ("mcsp:scopenode", 2, 0, 0, TNF_NONE);
tag = tnode_newnodetag ("MCSPFIXPOINT", tnd, NTF_NONE);
```

  - Parser structures are described using a BNF or DFA notation:

one or more mcsp:events separated by commas

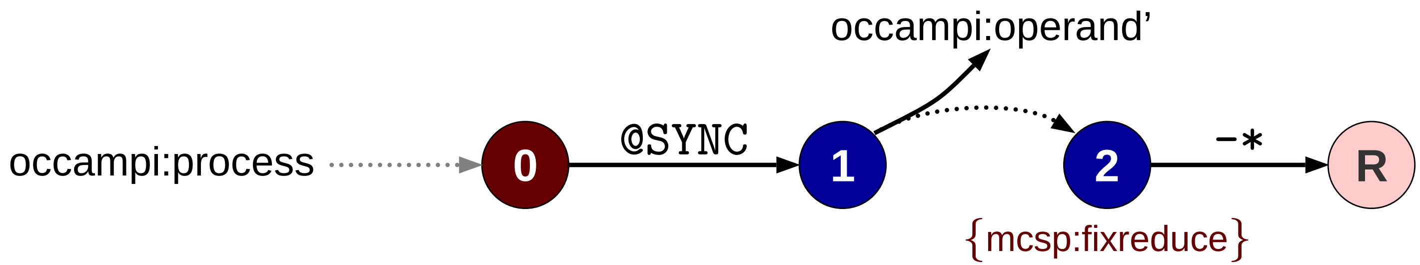
```
dynarray_add (transtbl, dfa_bnftotbl ("mcsp:eventset ::= "
          "( mcsp:event | @@{ { mcsp:event @@, 1 } @@} )"));
dynarray_add (transtbl, dfa_dfatotbl ("mcsp:fixpoint ::= "
          "[ 0 @@@ 1 ] [ 1 mcsp:name 2 ] [ 2 @@.  3 ] "
          "[ 3 mcsp:process 4 ] [ 4 {<mcsp:fixreduce>} -* ]"));
```



The New occam-π Compiler

- The compiler will typically need to process **several hundred** of these rules
  - takes an insignificant amount of time — efficient implementation :-)
  - currently fed from constant strings in C function calls, will use a text file in the future — real-time compiler compiler
- Rules already set can be augmented by language features (plug-in modules):

```
dynarray_add (transtbl, dfa_dfatotbl ("occampi:process +:= "
            "[ 0 @SYNC 1 ] [ 1 occampi:operand 2 ] "
            "[ 2 {<opi:syncreduce>} -* ]"));
```



- Compiler collects up DFA chunks, in **tables** and merges
  - later resolution of **sub-parses** (branches out of the DFA)

The New occam-π Compiler

- The reductions `{<mcsp:fixreduce>}` and `{<occampi:syncreduce>}` are pre-registered **generic reductions**:

```
parser_register_grule ("occampi:syncreduce",
            parser_decode_grule ("SNON+C1R-", opi.tag_SYNC));
```

- The 'program' is for a small stack machine which can manipulate the **DFA state**
  - can also make calls to C functions for more complex reductions
- Eventually all soaked up from a text file:

```
keyword "SYNC"
nodetype occampi:actionnode 3,0,0            # LHS, R
nodetag occampi:sync "occampi:actionnode"
reduce opi:syncreduce "SNON+00C[occampi:sync]3R-"
dfarule occampi:process {
            0:  "@SYNC" -> 1
            1:  "occampi:operand" -> 2
            2:  "<opi:syncreduce>" "-*" -> return
}
```

```
# incase things weren't getting silly yet:
keyword "bnfrule"
nodetype nocc:bnfrulenode 2,0,0
nodetag nocc:bnfrule "nocc:bnfrulenode"
dfarule nocc:compilerdef {
         0:  "@bnfrule" -> 1
         1:  "+Name" -> 2
         2:  "+String" -> 3
         3:  "Newline" -> return
         3:  cfunc ("noccparser_bnfreduce")
}
```

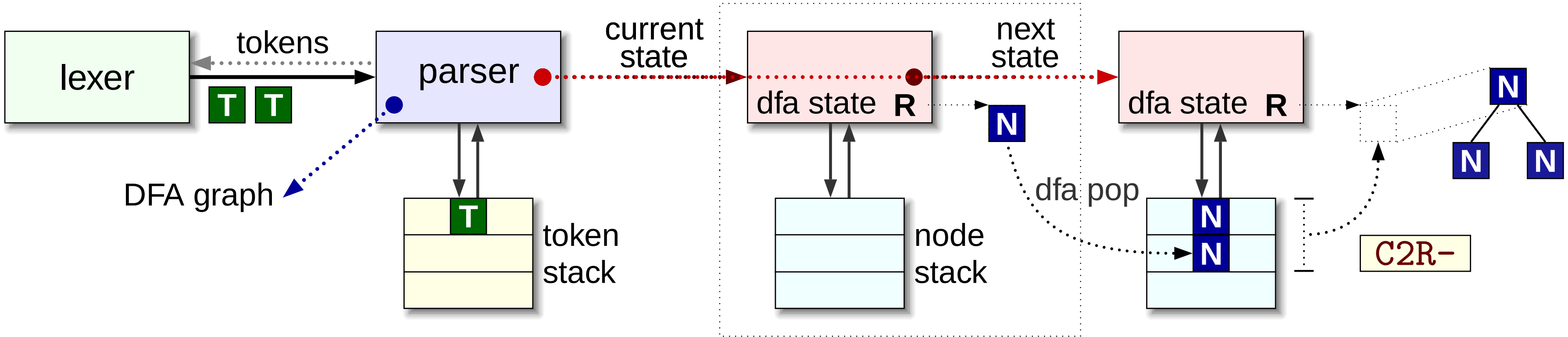
The New occam-π Compiler

- Once all the DFAs are set up (choice may depend on language being parsed), language-specific code will parse input with, e.g.:

```
parsetree = dfa_walk (lf, "occampi:declorprocstart");
```

('lf' is a reference to a lexer which provides the tokens)

- The **DFA engine** is what walks round the DFAs, using tokens from the lexer and maintaining a stack of **DFA states**
  - tokens can be pushed back into the lexer — useful for occam-π, which requires up to 3 look-aheads to determine what is being parsed



The New occam-π Compiler

- Knowing a bit about how the DFA engine operates helps to make sense of the language definitions:

push token onto the parser's token stack

reduce with the generic reduction ‘rfoo’

push token back into the lexer

match all initial matches from DFA rule ‘foo’

```
[ 0 +@FOO 1 ] [ 1 @@:= 2 ] [ 1 {<rfoo>} ] [ 2 -String <bar> ] [ 2 %foo 1 ]
```

match ‘FOO’ keyword

match assignment symbol

match quoted string

target state is the initial state of DFA rule ‘bar’

- The frequently occuring ‘`-*`’ means match anything and push back into the lexer
  - the ‘any’ match is special in that it is always tested last – **default match**
- DFA edges (matched **transitions**) with no target pop the DFA state
- Parser for a null language: `mylang ::= [ 0 * 0 ] [ 0 End ]`

The New occam-π Compiler

- The end result of the parser is a **parse tree**
  - this is then transformed by each pass of the compiler in turn
- Code that implements a language front-end can attach C functions to each pass
- Because the whole thing hangs together using structures containing function pointers, easy for code to intercept these and selectively override
  - not entirely unlike **aspect orientation**, albeit quite explicit
  - e.g. code for the occam-π multiway synchronisation inteferes with '`occampi:actionnode`', handling '`SYNC`' only and passing everything else along to whatever else was there before
- Last interesting pass for most of a language front-end is **name-map**, which inserts back-end specific nodes into the tree

Compiling CSP

- The syntax used is not quite the same as that used by FDR, but this may be changed later on:

	CSP	MCSP
skip	$SKIP$	`SKIP`
stop	$STOP$	`STOP`
chaos	$CHAOS$	`CHAOS`
divergence	div	`DIV`
event prefix	$e \longrightarrow P$	`e -> P`
internal choice	$(x \longrightarrow P) \sqcap (y \longrightarrow Q)$	`(x -> P) |~| (y -> Q)`
external choice	$(x \longrightarrow P) \Box (y \longrightarrow Q)$	`(x -> P) [] (y -> Q)`
sequence	$P \fatsemi Q$	`P; Q`
parallel	$P \parallel Q$	`P || Q`
interleaving	$P \interleave Q$	`P ||| Q`
hiding	$P \setminus \{a\}$	`P \ {a}`
fixpoint	$\mu X.P$	`@X.P`

Compiling CSP

- Using all the DFA paraphernalia, the compiler turns MCSP input into parse trees
  - at the top-level, named process definitions are expected:

```
P ::= s -> SKIP
Q (e) ::= ((e -> P) [] (f -> Q(e))) \ {f}
FOO (x) ::= x -> x -> Q ; STOP
```

- As with occam-π, the last process definition is used for the ‘top-level’ process
  - in parallel with this, the compiler generates an ‘environment’ process. Slightly artificial, but required to produce output:

```
ENVIRONMENT (out,x) ::= @z.(x -> out!"x*n" -> z)
SYSTEM (screen) ::= (FOO (k) || ENVIRONMENT (screen,k)) \ {k}
```

- Unbound events are captured by parameters, e.g.:

```
P (P_s) ::= P_s -> SKIP
Q (Q_P_s, e) ::= ((e -> P(Q_P_s)) [] (f -> Q(Q_P_s,e))) \ {f}
```

Interleaving Multiway Synchronisations

- Most of the required run-time mechanisms for executing CSP programs are already present in the KRoC system
  - no support for **interleaving** multiway synchroni

```
BISCUIT (coin) ::= coin -> biscuit -> SKIP
CHOC (coin) ::= coin -> choc -> SKIP
MACHINE (coin) ::= @x.((BISCUIT(coin) ||| CHOC(coin)) -> x)
```

instead we could have written:

```
MACHINE (coin) ::=
   @x.(coin ->
       (biscuit |~| choc); x)
```

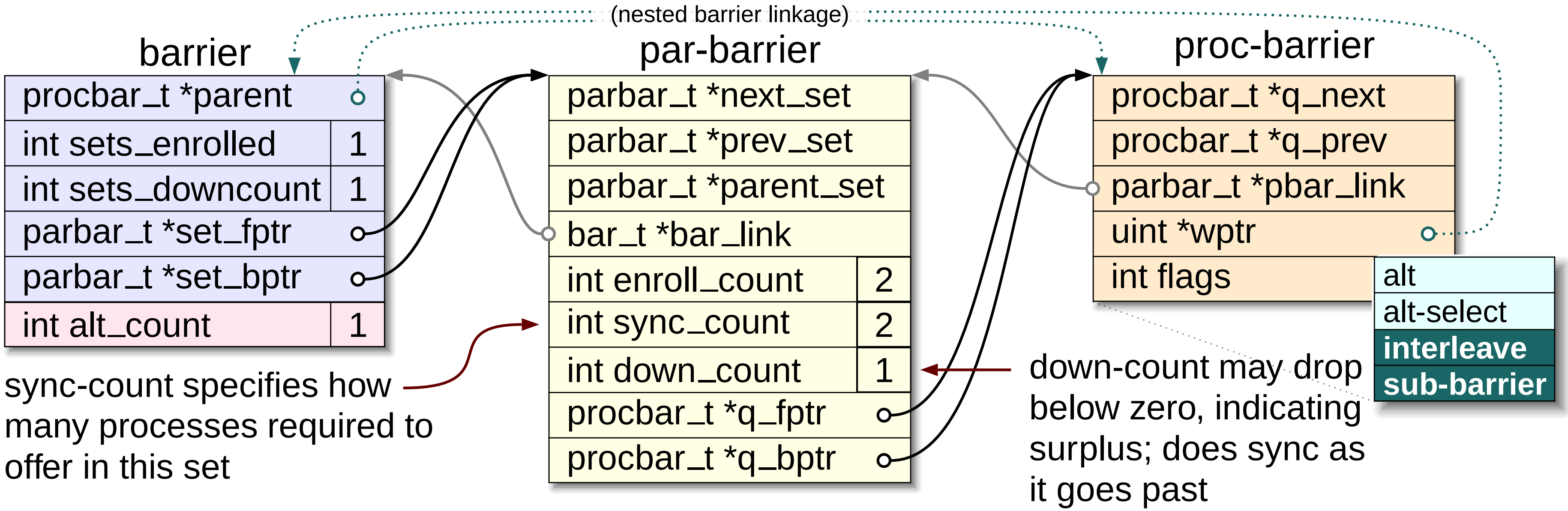
- Any multiway synchronisation (or part thereof) falls into 1 of 3 categories:
  - **1 of N**: the CSP model (strictly speaking ||| is a binary operator, N = 2, but NOCC will flatten nested interleaving)
  - **M of N**: where $1 < M < N$, useful for some implementations (aside later)
  - **N of N**: full synchronisation (typical occam-π '`BARRIER`' type)
- Only really need to support 1-of-N and N-of-N for MCSP, but would like the other cases for occam-π — same underlying implementation

Interleaving Multiway Synchronisations

- Support for these have now (just!) been added to the run-time
  - based on the non-interleaving version presented by Welch
  - only used by the occam-π front-end in NOCC, but expect MCSP to be using it before long — provided as a **language independent** feature
- Instead of having a single queue of blocked (**waiting-to-sync**) processes, groups processes into sets with **enroll**, **sync**, **down** counts and a queue
  - top-level barrier structure counts the number of enrolled sets and the number of sets left to synchronise
  - also a small structure associated with each synchronising process
- In most cases will have up to two levels of synchronisation
  - synchronisation completed in one of the **sets**
  - synchronisation completed at the top-level

Interleaving Multiway Synchronisations

- Compiler allocates structures in process workspaces in the **mwsynctrans** pass
  - new set of instructions in the run-time to manage these

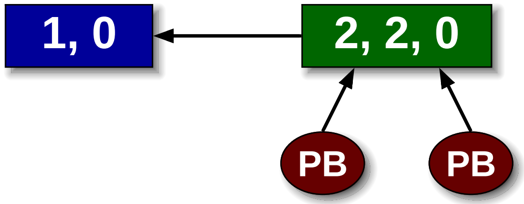


- Still uses a global lock around `ALT`s — to make sure that affected disabling sequences complete before more multiway synchronisations start
- Certain cases of interleaving require nesting of these (or do they...)
  - only when interleaving processes go sub-parallel or sub-interleave

Interleaving Multiway Synchronisations

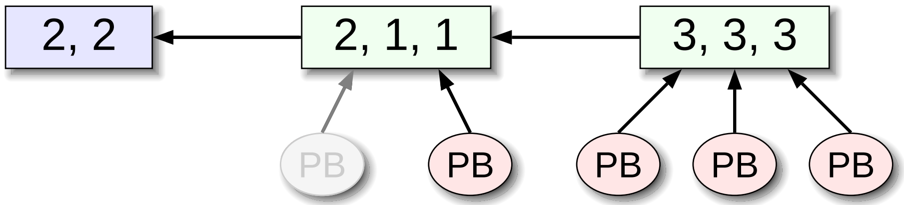
- Slightly non-trivial implementation, but can be reasoned about in pictures:

```
BARRIER b:
PAR
  P (b)
  Q (b)
```



P synchronises first
then Q synchronises,
completing the local barrier
which then completes
the top-level barrier

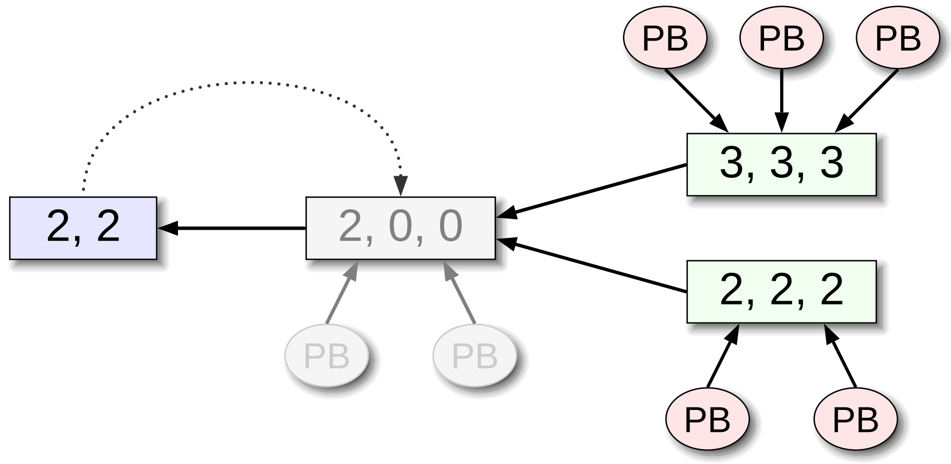
- Completed synchronisation resets top-level count, and in each synchronised barrier set, adds sync-count to down-count:



- Sub-parallelism (or interleaving) creates a logically upside-down tree; if P goes parallel with 3 sub-processes, its own is resigned

Interleaving Multiway Synchronisations

- If the other branch (Q) goes parallel simultaneously:



  - nothing left in the original set (sync-count reached zero), so it is **resigned** from the top-level
  - still 2 processes enrolled, so it doesn't go away entirely

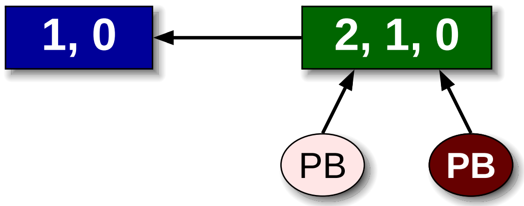
- When one of the parallel sub-processes shuts down, **re-enrolled** in its parent set
  - essentially the reverse process to setting up parallel processes, except that for occam-π (not MCSP) individual process 'PB's resign when the process terminates, not after the '`PAR`' (can be overridden with a compiler flag)

- Implementation currently leaves the disabled set attached to the linked-list of sets, could remove it if we wanted ...

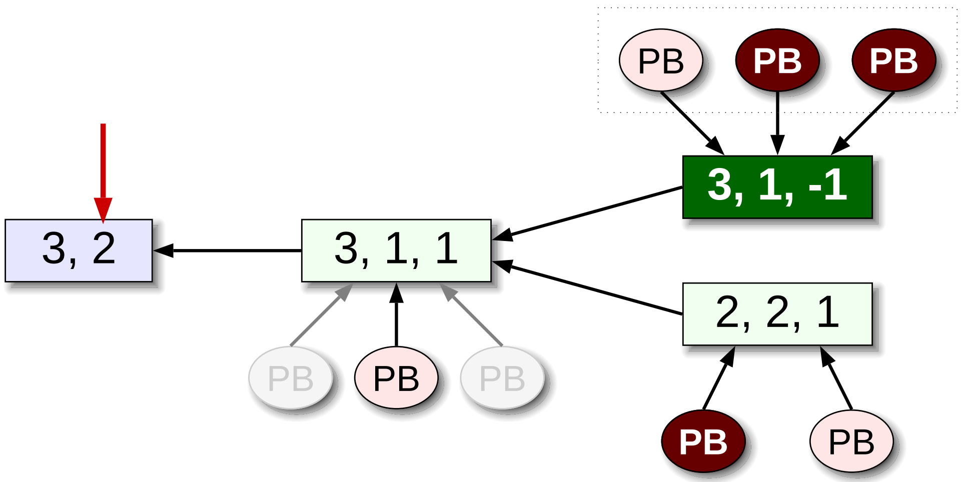
Interleaving Multiway Synchronisations

- Straight-forward interleaving (1-of-N) is handled by fixing the sync-count at 1:

```
(P (b) ||| Q (b)) \ {b}
```



- First process to synchronise will complete the barrier
- This works fine, provided that the interleaving sub-processes (P and Q) do not themselves go parallel or interleave
  - can have any amount of parallelism 'above' interleaving, e.g.:

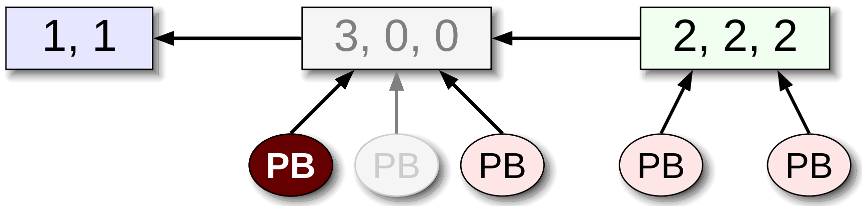


- Two sets left to synchronise
- When complete, only one of the interleaving processes will be resumed (queue implementation provides fairness); set remains ready

Interleaving Multiway Synchronisations

- This mechanism breaks down when interleaving processes go parallel, e.g.:

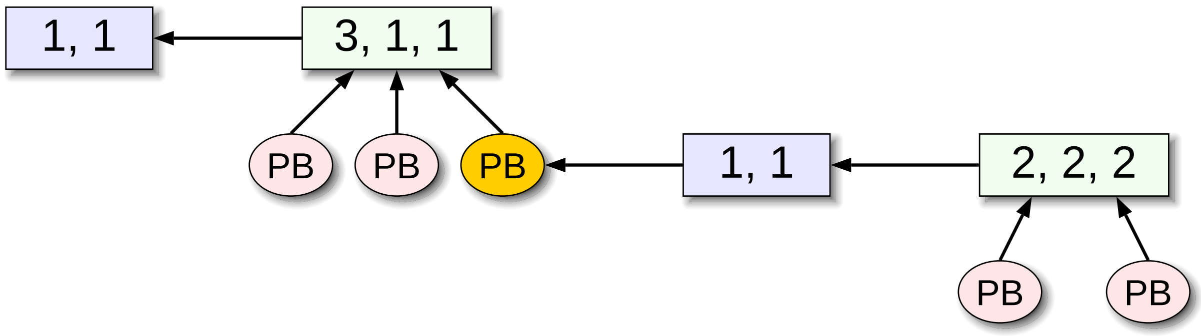
```
Q(b) ::= R (b) || S (b)
(P(b) ||| Q(b) ||| R(b)) \ {b}
```



- The existing route would see sync-count at zero and disable the set
  - problem arises when one of the interleaving processes synchronises
- Set is effectively inactive, so processes here won't be rescheduled — and don't know how to reset down-count (because sync-count now zero)
- Also the top-level sync may never occur because down-count is already at zero
- An early thought at a solution was to introduce a **missing-count**, separate to sync-count, but this breaks down in **M-of-N** interleaving

Interleaving Multiway Synchronisations

- One functional solution is to use nested barriers, as is almost supported:



- Problem with this solution is the run-time overhead — **proc-barrier** operations will need to test for sub-barriers and handle accordingly
- There may be a better solution, but haven't found it yet..

Interleaving Multiway Synchronisations (aside)

- The occam-π front-end in NOCC uses this mechanism to implement its `BARRIER` functionality
- Provides a nice solution to the classic **santa-claus** problem, still thinking about the language binding..:

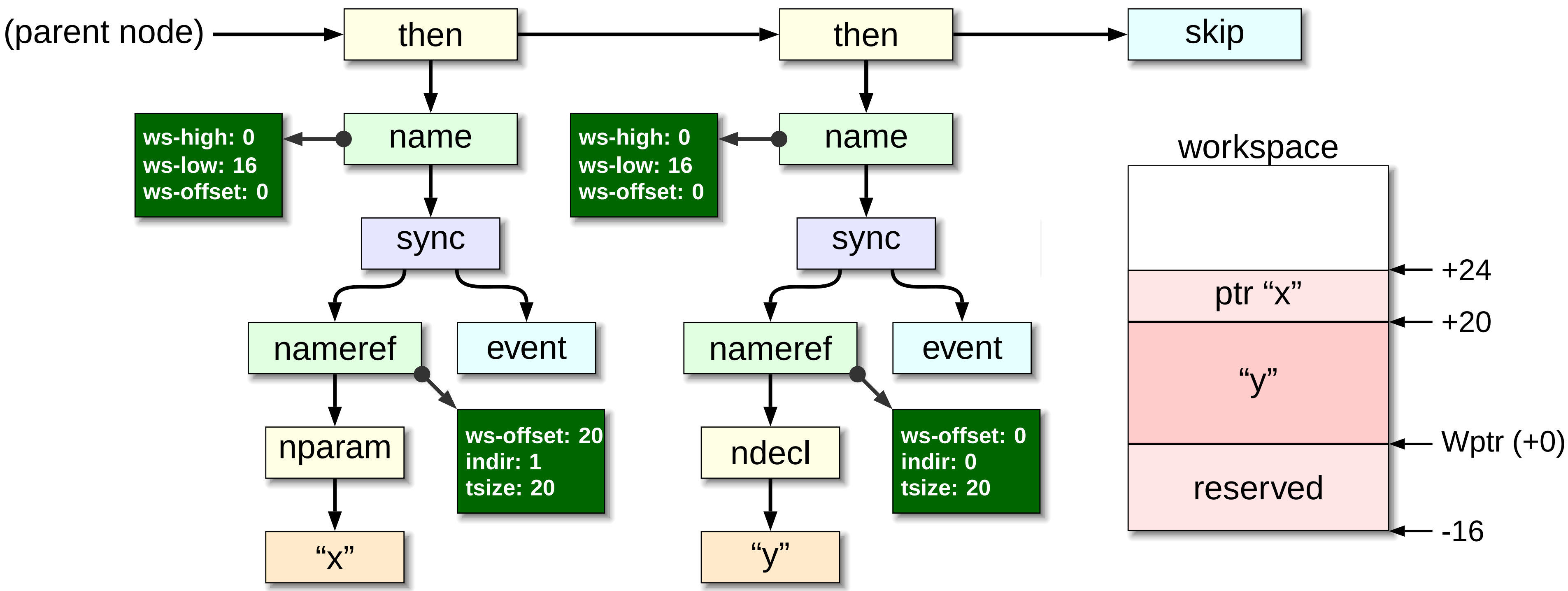
```
BARRIER e.sync:
BARRIER r.sync:
PAR
  santa (e.sync, r.sync)
  PAR i = 0 FOR 9
    reindeer (r.sync)
  PAR i = 0 FOR 10 INTERLEAVE e.sync(3)
    elf (e.sync)
```

```
PROC santa (BARRIER elves, reindeer)
  WHILE TRUE
    PRI ALT
      elves
        ...  meet with elves
      reindeer
        ...  go deliver presents
:
```

- Some outstanding issues relating to the **sync-count** when processes resign **in-par** — e.g. when there are only 2 elves left, are they allowed to meet with santa ?

Generating Code

- Once the parse tree has been built, the rest is mostly tree-transformations
- The compiler's `target_t` structure defines various back-end specific nodes
  - inserted during the **name-map** pass
- Starting with the code fragment `x -> y -> SKIP` :



Generating Code

- The compiler produces virtual transputer assembler as output, e.g.:

```
; PROCESS CONSUME = 44,28,12
.setws 44, 12
.setvs 0
.setms 0
.setnamedlabel "O_CONSUME"
.procentry "CONSUME"
.setlabel 7
    ajw   -16
.setlabel 59
    ldc   1
    stl   8
    ldc   1000000
    adc   -1
    stl   12
    ...
```

(all offsets/sizes in bytes to avoid word-size confusions)

```
<?xml version="1.0" encoding="iso-8859-1"?>
<nocc:libinfo version="0.1.4">
  <library name="commstime" namespace="">
    <libunit name="commstime.occ">
      <signedhash hashalgo="sha256" value="28373a..." />
      <proc name="CONSUME" language="mcsp"
          target="etc-kroc-unknown">
        <descriptor value="CONSUME(in,report)" />
        <blockinfo allocws="44" adjust="12" />
      </proc>
      ...  other processes
    </libunit>
  </library>
</nocc:libinfo>
```

- Eaten up by **tranx86**, assembled and linked with the **CCSP** runtime
- Compiler also produces meta-data files (for use with separate compilation, etc.)

Performance

- Have an MCSP version of the commstime benchmark:
  - actually measuring the multiway synchronisation time

```
PREFIX (in,out)        ::= out -> @x.(in -> out -> x)
SUCC (in,out)          ::= @x.(in -> out -> x)
DELTA (in,out1,out2)   ::= @x.(in -> out1 -> out2 -> x)
CONSUME (in,report)    ::= @x.((;[i=1,1000000] in); report -> x)

COMMSTIME (report) ::= ((PREFIX (a,b) || DELTA (b,c,d)) ||
                        (SUCC (c,a) || CONSUME (d,report))) \ {a,b,c,d}
```

- Because there are currently no timer facilities, have to rely on the time between ‘report’ outputs (every million cycles)
  - on a 2.4 GHz P4, time for a complete synchronisation with 2 process is approximately 250 nanoseconds (syncs implemented as single-guard `ALT`s) (using Welch’s algorithm with dynamic wait-queue allocation)

Conclusions and Further Work

- The compiler currently manages most **simple** MCSP programs
  - some features still not implemented: replicated parallel/interleaving, alphabetised parallel, variables/expressions, interrupts, timers
  - and some restrictions: **no** self/mutual recursion, **no** non-tail-call fixpoints
- The MCSP specific part of NOCC weighs in at around **6,000** lines of C code
  - not huge considering, and relatively easy to maintain
- Items for future consideration:
  - different **environments** — e.g. for graphical visualisations
  - adjustment of the syntax for FDR compatibility