SyncCharts in C

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EMSOFT'09, Grenoble, 13 October 2009

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A Proposal for Light-Weight, Deterministic Concurrency

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Light-Weight, Deterministic Concurrency in C

If you insist, you can use it for SyncCharts . . .

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Problem Statement

Given:
C compiler (preferrably gcc)

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C compiler (preferrably gcc) + programmer that knows C

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What we want:

Deterministic concurrency

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What we want:

Deterministic concurrency . . . and maybe preemption, deadlock avoidance, signal handling, instantaneous communication, dynamic priorities, proper handling of schizophrenia, etc.

Problem Statement

Given:

C compiler (preferrably gcc) + programmer that knows C

What we want:

Deterministic concurrency . . . and maybe preemption, deadlock avoidance, signal handling, instantaneous communication, dynamic priorities, proper handling of schizophrenia, etc.

What we don't want:

Heavy tools, special compilers, licenses, training courses, OS overhead, custom hardware, platform dependence, adaptation effort, . . .

Problem Statement

Want to *embed* deterministic, concurrent semantics in traditional, sequential language (C)

Embedding means:

- Just add language constructs that can be expressed in C
- Do *not* restrict/change/extend semantics of C language
- Do *not* require separate preprocessors, analysis tools or compilers

Overview

Motivating Example: Producer-Consumer-Observer

Precision Timed Architecture (PRET):

- Uses physical time to synchronize (DEAD instruction)
- Current programming model requires analysis of code + execution platform

Producer

```
int main() {
  DEAD(28);
  volatile unsigned int * buf =
       (unsigned int*)(0x3F800200);
  unsigned int i = 0;
  for (i = 0; ; i++ ) {
    DEAD(26);
    *buf = i;
  }
  return 0;
}
```

Consumer

```
int main() {
  DEAD(41);
  volatile unsigned int * buf =
       (unsigned int*)(0x3F800200);
  unsigned int i = 0;
  int arr[8];
  for (i =0; i<8; i++)
    arr[i] = 0;
  for (i = 0; ; i++) {
    DEAD(26);
    register int tmp = *buf;
    arr[i%8] = tmp;
  }
  return 0;
}
```

Observer

```
int main() {
  DEAD(41);
  volatile unsigned int * buf =
       (unsigned int*)(0x3F800200);
  volatile unsigned int * fd =
       (unsigned int*)(0x80000600);
  unsigned int i = 0;
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    DEAD(26);
    *fd = *buf;
  }
  return 0;
}
```

Lickly *et al.*, CASES'08

Overview

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  return 0;
}
```

```c
#include "sc.h"

// == MAIN FUNCTION ==
int main()
{
  int notDone, init = 1;

  do {
    notDone = tick(init);
    //sleep(1);
    init = 0;
  } while (notDone);
  return 0;
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Producer

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    init = 0;
  } while (notDone);
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}

// == TICK FUNCTION ==
int tick(int isInit )
{
  static int BUF, fd, i, j,
    k = 0, tmp, arr [8];

  TICKSTART(isInit, 1);

 PCO:
  FORK(Producer, 3);
  FORK(Consumer, 2);
  FORKE(Observer);

 Producer:
  for (i = 0; ; i++) {
    PAUSE;
    BUF = i; }


 Consumer:
  for (j = 0; j < 8; j++)
    arr[j] = 0;
  for (j = 0; ; j++) {
    PAUSE;
    tmp = BUF;
    arr[j % 8] = tmp; }

 Observer:
  for ( ; ; ) {
    PAUSE;
    fd = BUF;
    k++; }

  TICKEND;
}
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    arr[j] = 0;
  for (j = 0; ; j++) {
    PAUSE;
    tmp = BUF;
    arr[j % 8] = tmp; }

 Observer:
  for ( ; ; ) {
    PAUSE;
    fd = BUF;
    k++; }

  TICKEND;
}
```

Dynamic Coroutines

Approach: Manage threads at application level

Problem: C does not provide access to program counter

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Problem: C does not provide access to program counter

Solution: Program labels + computed goto

- All possible continuation points of a thread get an ordinary C label
- For each thread, maintain a coarse program counter that points to continuation label

SC Thread Operators

TICKSTART*(*init*, *p*)	Start (initial) tick, assign main thread priority *p*.
TICKEND	Return true (1) iff there is still an enabled thread.

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PAUSE*+	Deactivate current thread for this tick.
TERM*	Terminate current thread.
ABORT	Abort descendant threads.
TRANS(*l*)	Shorthand for ABORT; GOTO(*l*).
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FORK(*l*, *p*)	Create a thread with start address *l* and priority *p*.
FORKE*(*l*)	Finalize FORK, resume at *l*.
JOINELSE*+(l_{else})	If descendant threads have terminated normally, proceed; else pause, jump to l_{else}.
JOIN*+	Waits for descendant threads to terminated normally. Shorthand for l_{else}: JOINE(l_{else}).
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* possible thread dispatcher call

\+ automatically generates continuation label

Overview

Recall: Producer-Consumer-Observer in SC

```
#include "sc.h"

// == MAIN FUNCTION ==
int main()
{
  int notDone, init = 1;

  do {
    notDone = tick( init );
    //sleep(1);
    init = 0;
  } while (notDone);
  return 0;
}

// == TICK FUNCTION ==
int tick( int isInit )
{
  static int BUF, fd, i, j,
    k = 0, tmp, arr[8];

  TICKSTART(isInit, 1);

 PCO:
  FORK(Producer, 3);
  FORK(Consumer, 2);
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 Producer:
  for (i = 0; ; i++) {
    PAUSE;
    BUF = i; }

 Consumer:
  for (j = 0; j < 8; j++)
    arr[j] = 0;
  for (j = 0; ; j++) {
    PAUSE;
    tmp = BUF;
    arr[j % 8] = tmp; }

 Observer:
  for ( ; ; ) {
    PAUSE;
    fd = BUF;
    k++; }

  TICKEND;
}
```

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 Producer:
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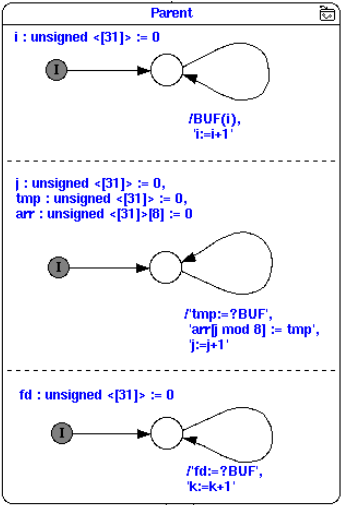
  for (j = 0; j < 8; j++)
    arr[j] = 0;
  for (j = 0; ; j++) {
    PAUSE;
    tmp = BUF;
    arr[j % 8] = tmp; }

 Observer:
  for ( ; ; ) {
    PAUSE;
    fd = BUF;
    k++; }

  TICKEND;
}
```



Producer-Consumer-Observer + Preemptions

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// == MAIN FUNCTION ==
int main()
{
  int notDone, init = 1;

  do {
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    //sleep(1);
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  } while (notDone);
  return 0;
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 PCO:
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 Producer:
  for (i = 0; ; i++) {
    PAUSE;
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 Consumer:
  for (j = 0; j < 8; j++)
    arr[j] = 0;
  for (j = 0; ; j++) {
    PAUSE;
    tmp = BUF;
    arr[j % 8] = tmp; }

 Observer:
  for ( ; ; ) {
    PAUSE;
    fd = BUF;
    k++; }

  TICKEND;
}
```
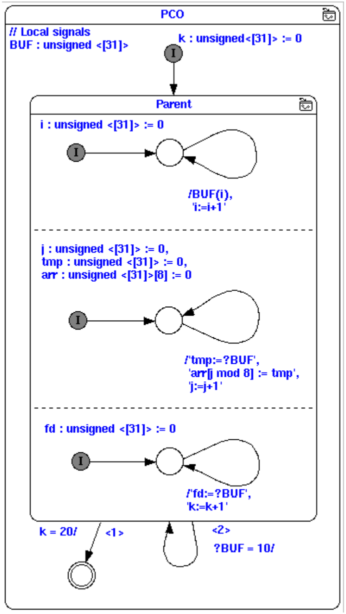
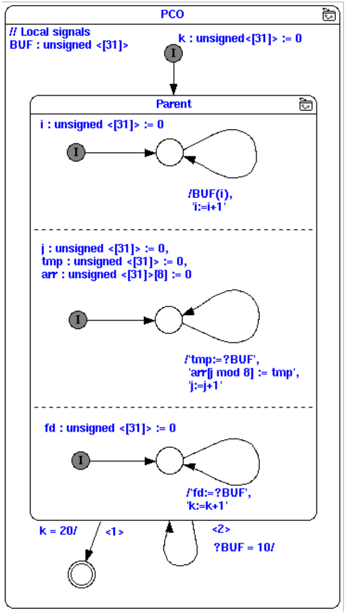
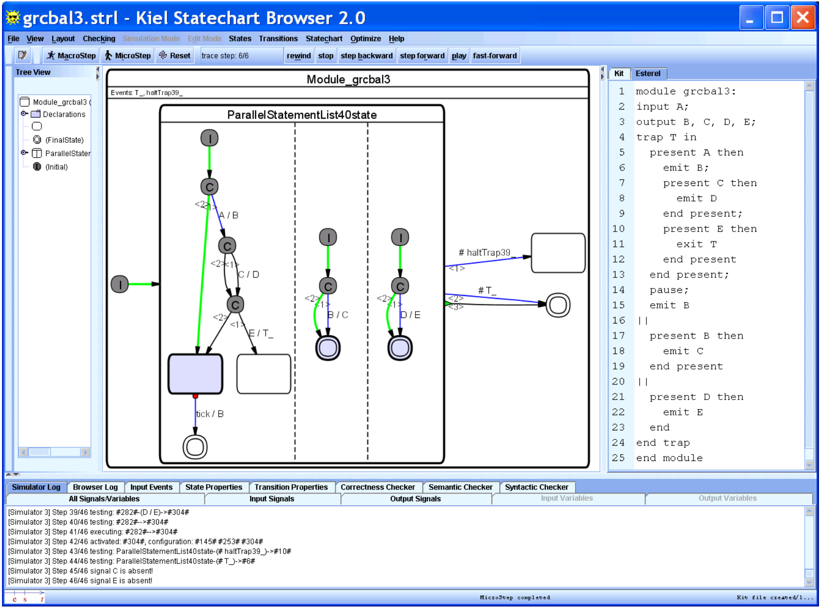



Producer-Consumer-Observer + Preemptions

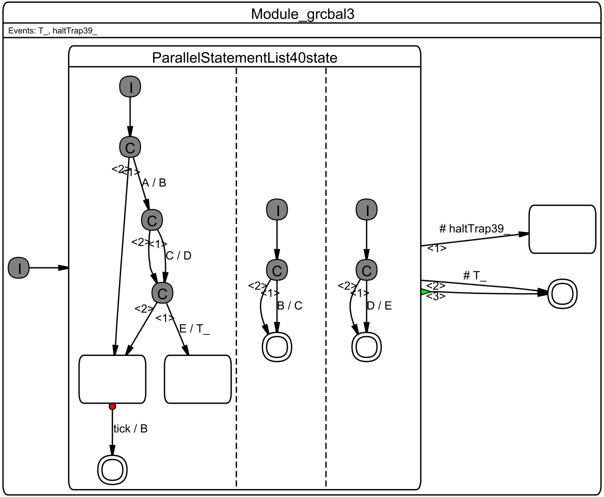
```
#include "sc.h"

// == MAIN FUNCTION ==
int main()
{
  int notDone, init = 1;

  do {
    notDone = tick(init);
    //sleep(1);
    init = 0;
  } while (notDone);
  return 0;
}

// == TICK FUNCTION ==
int tick(int isInit)
{
  static int BUF, fd, i, j,
    k = 0, tmp, arr[8];

  TICKSTART(isInit, 1);

 PCO:
  FORK(Producer, 4);
  FORK(Consumer, 2);
  FORK(Observer, 3);
  FORKE(Parent);
 Producer:
  for (i = 0; ; i++) {
    PAUSE;
    BUF = i; }

 Consumer:
  for (j = 0; j < 8; j++)
    arr[j] = 0;
  for (j = 0; ; j++) {
    PAUSE;
    tmp = BUF;
    arr[j % 8] = tmp; }

 Observer:
  for ( ; ; ) {
    PAUSE;
    fd = BUF;
    k++; }

 Parent:
  while (1) {
    PAUSE;
    if (k == 20)
      TRANS(Done);
    if (BUF == 10)
      TRANS(PCO);
  }

 Done:
  TERM;
  TICKEND;
}
```





Edwards *et al.*, JES'07; Prochnow *et al.*, LCTES'06

```
 TICKSTART(isInit, 1);
 FORK(T1, 6);
 FORK(T2, 5);
 FORK(T3, 3);
 FORKE(TMain);

T1: if (PRESENT(A)) {
    EMIT(B);
    PRIO(4);
    if (PRESENT(C))
      EMIT(D);
    PRIO(2);
    if (PRESENT(E)) {
      EMIT(T_);
      TERM; }
  }
 PAUSE;
 EMIT(B);
 TERM;

T2: if (PRESENT(B))
    EMIT(C);
 TERM;

T3: if (PRESENT(D))
    EMIT(E);
 TERM;

TMain: if (PRESENT(T_)) {
    ABORT;
    TERM; }
 JOINELSE(TMain);
 TICKEND;
```



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   if (PRESENT(C))
     EMIT(D);
   PRIO(2);
   if (PRESENT(E)) {
     EMIT(T_);
     TERM; }
 }
 PAUSE;
 EMIT(B);
 TERM;

T2: if (PRESENT(B))
   EMIT(C);
 TERM;

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 TERM;

TMain: if (PRESENT(T_)) {
   ABORT;
   TERM; }
 JOINELSE(TMain);
 TICKEND;
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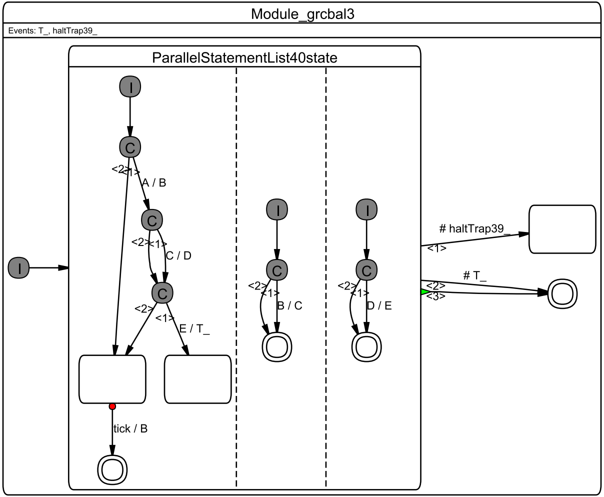

Sample Execution

```
 TICKSTART(isInit, 1);
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     EMIT(T_);
     TERM; }
 }
 PAUSE;
 EMIT(B);
 TERM;

T2: if (PRESENT(B))
   EMIT(C);
 TERM;

T3: if (PRESENT(D))
   EMIT(E);
 TERM;

TMain: if (PRESENT(T_)) {
   ABORT;
   TERM; }
 JOINELSE(TMain);
 TICKEND;
```

```
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  }
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T2: if (PRESENT(B))
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  TERM;

T3: if (PRESENT(D))
    EMIT(E);
  TERM;

TMain: if (PRESENT(T_)) {
    ABORT;
    TERM; }
  JOINELSE(TMain);
  TICKEND;
```

Sample Execution

```
==== TICK 0 STARTS, inputs = 01, enabled = 00
==== Inputs (id/name): 0/A
==== Enabled (id/state): <init>
FORK:    1/<init> forks 6/T1, active = 0103
FORK:    1/<init> forks 5/T2, active = 0143
FORK:    1/<init> forks 3/T3, active = 0153
FORKE:   1/<init>
PRESENT: 6/T1 determines A/0 as present
EMIT:    6/T1 emits B/1
PRIO:    6/T1 set to priority 4
PRESENT: 5/T2 determines B/1 as present
EMIT:    5/T2 emits C/2
TERM:    5/T2 terminates, enabled = 073
PRESENT: 4/_L73 determines C/2 as present
EMIT:    4/_L73 emits D/3
PRIO:    4/_L73 set to priority 2
PRESENT: 3/T3 determines D/3 as present
EMIT:    3/T3 emits E/4
TERM:    3/T3 terminates, enabled = 017
PRESENT: 2/_L76 determines E/4 as present
EMIT:    2/_L76 emits T_/5
TERM:    2/_L76 terminates, enabled = 07
PRESENT: 1/TMain determines T_/5 as present
ABORT:   1/TMain disables 070, enabled = 03
TERM:    1/TMain terminates, enabled = 03
==== TICK 0 terminates after 22 instructions.
==== Enabled (id/state): 0/_L_TICKEND
==== Resulting signals (name/id): 0/A, 1/B, 2/C, 3/D, 4/E, 5/T_,
         Outputs OK.
```

Overview

How Light-Weight is It?

Program perspective

Thread management

- Context: PC (1 word), descs (1 thread bit vector), parent (1 thread id), active and enabled (2 bits in thread bitvector)
- Context switch: 1 BSR instruction (on x86) + array lookup

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Source code

- Very dense operator encoding

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- Context switch: 1 BSR instruction (on x86) + array lookup

Source code

- Very dense operator encoding

Executable

- Most operators translate to handful of assembler statements

How Light-Weight is It?

Programmer perspective

Installation effort

- Free download and documentation:
  `http://www.informatik.uni-kiel.de/rtsys/sc/`
- Total tar ball is $\approx$ 50 K, mostly examples
- Really need just sc.h (and, on non-x86, selectCid.c)
- No further tools or Makefile adaptations

How Light-Weight is It?

Programmer perspective

Installation effort

- Free download and documentation:
  `http://www.informatik.uni-kiel.de/rtsys/sc/`
- Total tar ball is $\approx$ 50 K, mostly examples
- Really need just sc.h (and, on non-x86, selectCid.c)
- No further tools or Makefile adaptations

Mental effort

- Operators needed to get started fit on one slide
- For exact understanding, can look at sc.h ($<$ 1 Kloc)

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SC Programming model

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Current implementation

- Uses computed goto (gcc)
- Thread sets represented as bit vectors (unsigned int)
- No. of threads limited by word size

Summary

SyncCharts in C

- Light-weight approach to embed deterministic reactive control flow constructs into widely used programming language
- Fairly small number of primitives suffices to cover all of SyncCharts
- Multi-threaded, priority-based approach inspired by synchronous reactive processing—where it required special hw + special compiler

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In the full report (on-line, at SC 1.5)

- Valued signals, PRE, suspension, schizophrenia handling
- Realization
- Many further examples

Where This Might be Going

SC can be used ...

- ... as programming language
- ... as intermediate target language for synthesizing graphical SyncChart models into tracable executable code
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Questions/Comments?

Appendix

Overview

Explaining the (Original) Title: SyncCharts ...

Reactive control flow:

- Sequentiality
- + Concurrency
- + Preemption

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SyncCharts [André 1996]:

- Statecharts concept
- + Synchronous semantics

...in C

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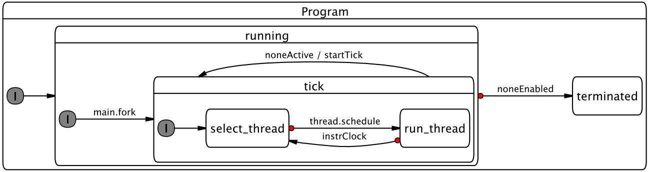
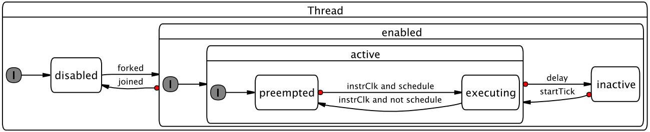
SyncCharts in C scenario: Use SC Operators

- ☺ Light weight to implement and to execute
- ☺ Just need regular compiler
- ☺ Semantics grounded in synchronous model

The inspiration: Reactive processing





Li *et al.*, ASPLOS'06

- SC multi-threading very close to Kiel Esterel Processor
- Difference: KEP dispatches at every instrClk, SC only at specific SC operators (such as PAUSE, PRIO)

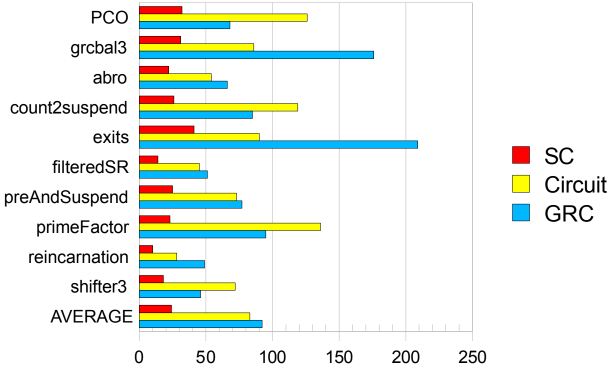
The SC Signal Operators

SIGNAL(S)	Initialize a local signal S.
EMIT(S)	Emit signal S.
PRESENT(S, l_{else})	If S is present, proceed normally; else, jump to l_{else}.
EMITINT(S, val)	Emit valued signal S, of type integer, with value val.
EMITINTMUL(S, val)	Emit valued signal S, of type integer, combined with multiplication, with value val.
VAL(S, reg)	Retrieve value of signal S, into register/variable reg.
PRESENTPRE(S, l_{else})	If S was present in previous tick, proceed normally; else, jump to l_{else}. If S is a signal local to thread t, consider last preceeding tick in which t was active, *i. e.*, not suspended.
VALPRE(S, reg)	Retrieve value of signal S at previous tick, into register/variable reg.

Further Operators

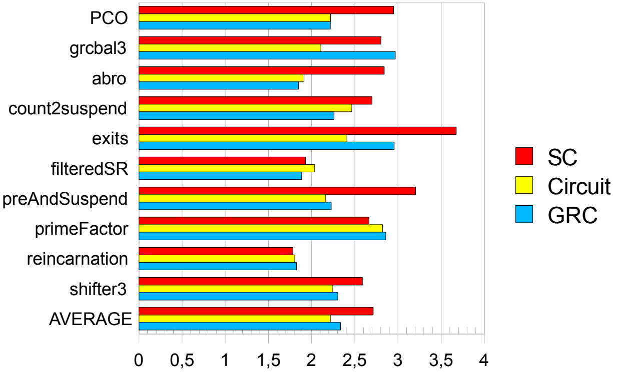
GOTO(l)	Jump to label l.
CALL(l, l_{ret})	Call function l (eg, an on exit function), return to l_{ret}.
RET	Return from function call.
ISAT(id, l_{state}, l)	If thread id is at state l_{state}, then proceed to next instruction (*e. g.*, an on exit function associated with id at state l_{state}). Else, jump to label l.
PPAUSE*(p, l)	Shorthand for PRIO(p, l'); l': PAUSE(l) (saves one call to dispatcher).
JPPAUSE*(p, l_{then}, l_{else})	Shorthand for JOIN(l_{then}, l); l: PPAUSE(p, l_{else}) (saves another call to dispatcher).
ISATCALL(id, l_{state}, l_{action}, l)	Shorthand for ISAT(id, l_{state}, l); CALL(l_{action}, l)

Conciseness



Size of tick function in C source code, line count without empty lines and comments

Code Size



Size of tick function object code, in Kbytes

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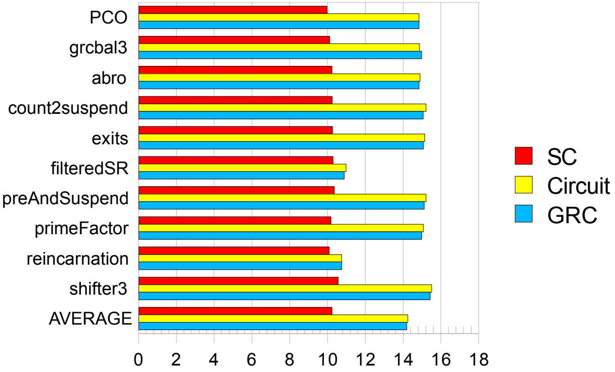
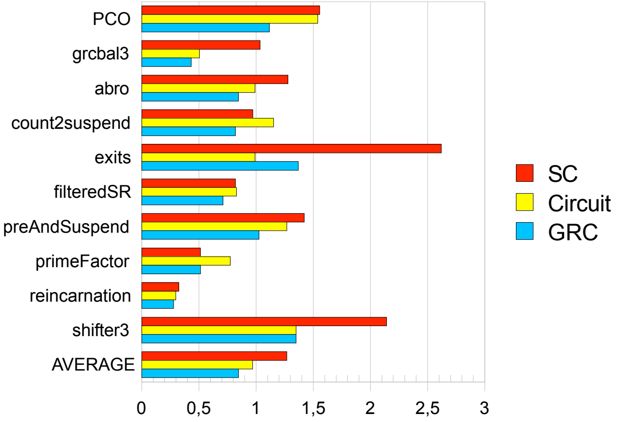


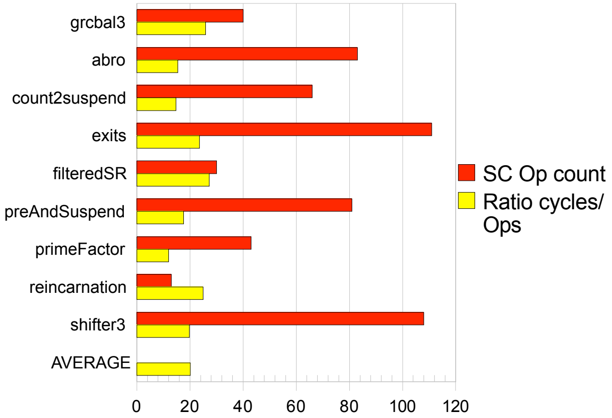
Size of executable, in Kbytes

Performance



Accumulated run times of tick function, in thousands of clock cycles

Operator Density



SC operations count, ratio to clock cycles

Related Work (Lots Of It . . .)

- Synchronous language extensions: Reactive C [Boussinot '91], ECL [Lavagno & Sentovich '99], FairThreads [Boussinot '06], Lusteral [Mendler & Pouzet '08]
- Compilation of synchronous programs [Berry, Edwards, Potop-Butucaru, . . .]
- BAL virtual machine [Edwards & Zeng '07]
- PRET [Edwards, Lee *et al.*'08], PRET-C [Roop *et al.*'09], SHIM [Tardieu & Edwards '06]
- Numerous Statechart dialects (Statemate, Stateflow, SCADE, ASCET, UML, . . .)
- Statecharts and FMSs in C/C++ [Samek '08, Wagner *et al.*'06]
- Compilation of Statecharts [Ali & Tanaka '00, Wasowski '03], SyncCharts [André '03]
- Compilation for reactive processors [Li *et al.*'06, Yuan *et al.*'08]