A Multi-Threaded Reactive Processor

Xin Li Marian Boldt *Reinhard v. Hanxleden*

Real-Time Systems and Embedded Systems Group
Department of Computer Science
Christian-Albrechts-Universität zu Kiel, Germany
`www.informatik.uni-kiel.de/rtsys`

ASPLOS'06
24 October 2006

Institut für Informatik
Christian-Albrechts-Universität zu Kiel

Reactive vs. Non-Reactive Systems

Transformational systems	*numerical computation programs, compilers . . .*
Interactive systems	*operating systems, databases . . .*

Reactive vs. Non-Reactive Systems

Transformational systems	*numerical computation programs, compilers . . .*
Interactive systems	*operating systems, databases . . .*
Reactive systems	*process controllers, signal processors . . .*

Why "Reactive Processing"?

Control flow on traditional (non-embedded) computing systems:

- Jumps, conditional branches, loops
- Procedure/method calls

Control flow on embedded, reactive systems: all of the above, plus

Why "Reactive Processing"?

Control flow on traditional (non-embedded) computing systems:

- Jumps, conditional branches, loops
- Procedure/method calls

Control flow on embedded, reactive systems: all of the above, plus

- Concurrency
- Preemption

Why "Reactive Processing"?

Control flow on traditional (non-embedded) computing systems:

- Jumps, conditional branches, loops
- Procedure/method calls

Control flow on embedded, reactive systems: all of the above, plus

- Concurrency
- Preemption

The problem: mismatch between traditional processing architectures and reactive control flow patterns

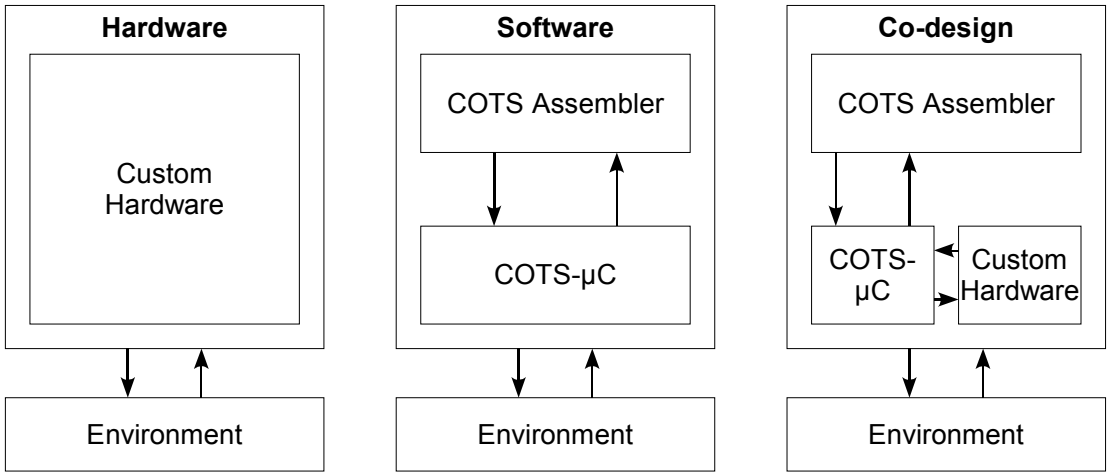
- Processing overhead, *e. g.* due to OS involvement or need to save thread states at application level
- Timing unpredictability

Reactive Processing Part I: The Language

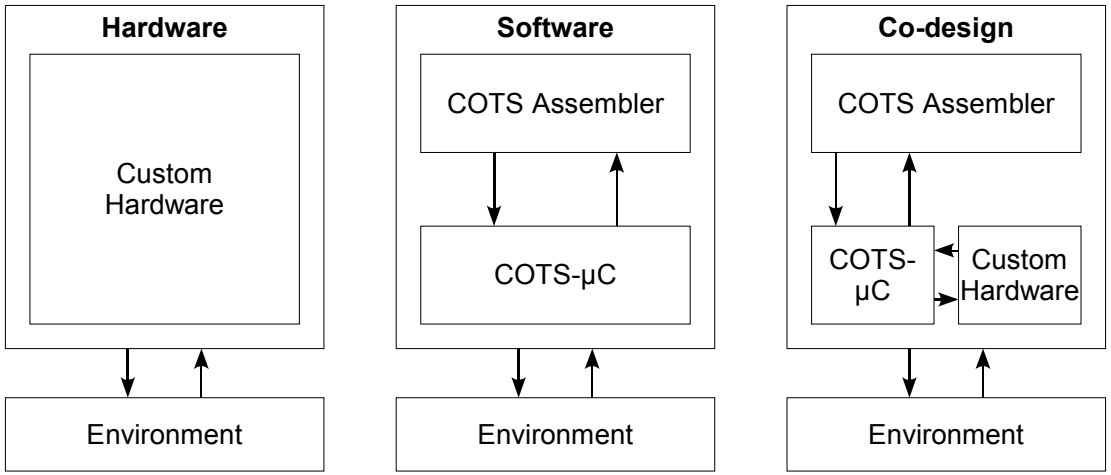
Have chosen **Esterel**:

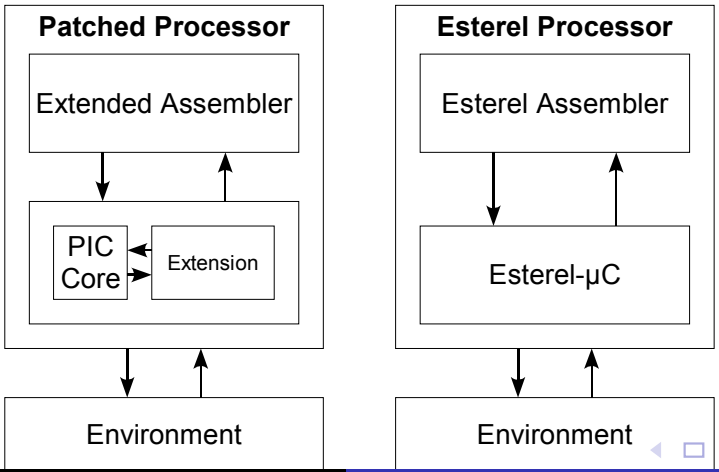
- Created in the early 1980's
- For programming control-dominated reactive systems
- Used as intermediate language for Statechart (Safe State Machines)
- Textual imperative language with reactive control flow constructs
  - Concurrency
  - Weak/strong abortion
  - Exceptions
  - Suspension
- A synchronous language
- Deterministic behavior, clean semantics
- Currently undergoing IEEE standardization

Reactive Processing Part II: The Execution Platform



Reactive Processing Part II: The Execution Platform





Why bother?

Reactive processing yields

- Low power requirements
- Deterministic control flow
- Predictable timing
- Short design cycle

Why bother?

Reactive processing yields

- Low power requirements
- Deterministic control flow
- Predictable timing
- Short design cycle

Can use reactive processor

- in stand alone, small reactive applications

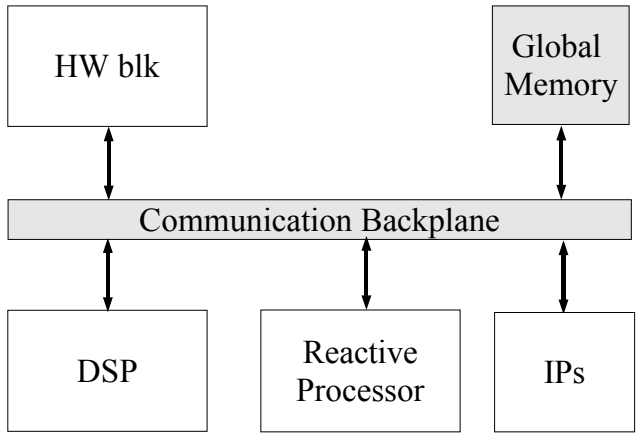
Why bother?

Reactive processing yields

- Low power requirements
- Deterministic control flow
- Predictable timing
- Short design cycle

Can use reactive processor

- in stand alone, small reactive applications
- as building block in SoC designs



Overview

The Esterel Language

Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

The Esterel Language

Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

```
module ABRO:
input A, B, R;
output O;
loop
  abort
    [ await A
     ||
      await B ];
    emit O
    halt;
  when R
end loop;
end module
```

The Esterel Language

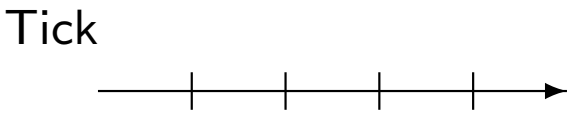
Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

```
module ABRO:
input A, B, R;
output O;
loop
  abort
    [ await A
     ||
      await B ];
    emit O
    halt;
  when R
end loop;
end module
```



The Esterel Language

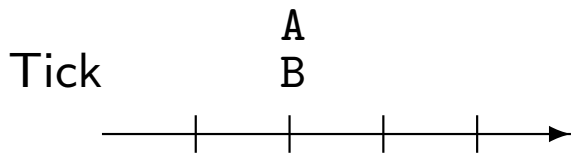
Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

```
module ABRO:
input A, B, R;
output O;
loop
  abort
    [ await A
     ||
      await B ];
    emit O
    halt;
  when R
end loop;
end module
```



The Esterel Language

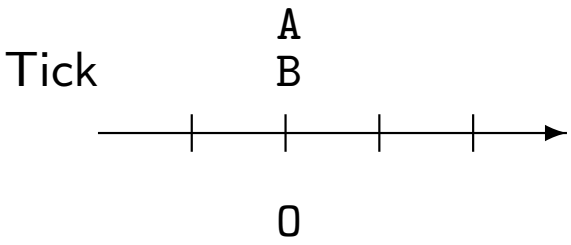
Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

```
module ABRO:
input A, B, R;
output O;
loop
  abort
    [ await A
     ||
      await B ];
    emit O
    halt;
  when R
end loop;
end module
```



The Esterel Language

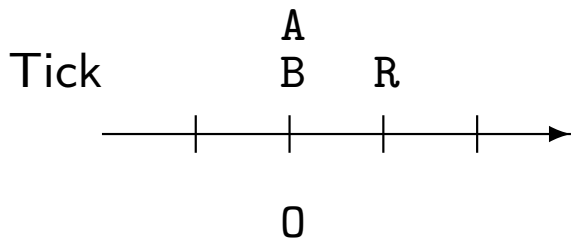
Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

```
module ABRO:
input A, B, R;
output O;
loop
  abort
    [ await A
     ||
      await B ];
    emit O
    halt;
  when R
end loop;
end module
```



The Esterel Language

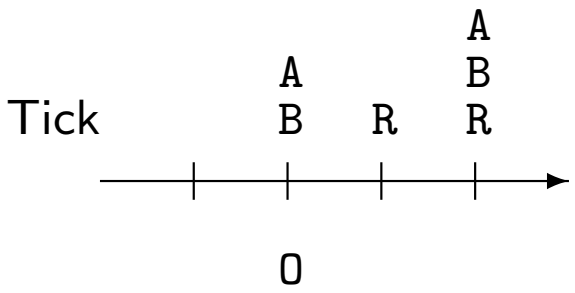
Logical Ticks

- Execution is divided into *ticks*
- Synchrony hypothesis:
  Outputs generated from given inputs occur at the same tick

Signals

- *Present* or *absent* throughout a tick
- Used to communicate internally and with the environment

```
module ABRO:
input A, B, R;
output O;
loop
  abort
    [ await A
     ||
      await B ];
    emit O
    halt;
  when R
end loop;
end module
```



Candidates for the Instruction Set

Esterel kernel statements

- `||`
- `suspend ... when` S
- `trap` T `in ... exit` T `... end trap`
- `pause`
- `signal` S `in ... end`
- `emit` S
- `present` S `then ... end`
- `nothing`
- `loop ... end loop`
- `;`

Candidates for the Instruction Set

Esterel kernel statements

- `||`
- `suspend ... when` S
- `trap` T `in ... exit` T `... end trap`
- `pause`
- `signal` S `in ... end`
- `emit` S
- `present` S `then ... end`
- `nothing`
- `loop ... end loop`
- `;`

Derived statements

- `[weak] abort ... when` S
- `await` S

The KEP Instruction Set

- Includes all kernel statements
- In addition, some derived statements
  This redundancy improves space/time efficiency

The KEP Instruction Set

- Includes all kernel statements
- In addition, some derived statements
  This redundancy improves space/time efficiency

```
TOS:                    % trap T in
A0:                     %  loop
    PAUSE               %   pause;
    PRESENT S,A1        %   present S then
      EXIT TOE, TOS     %    exit T
A1:                     %   end present
    GOTO A0             %  end loop
TOE:                    % end trap;
```

The KEP Instruction Set

- Includes all kernel statements
- In addition, some derived statements
  This redundancy improves space/time efficiency

```
TOS:                    % trap T in
A0:                     %  loop
    PAUSE               %   pause;
    PRESENT S,A1        %   present S then
      EXIT TOE, TOS     %    exit T
A1:                     %   end present
    GOTO A0             %  end loop
TOE:                    % end trap;
```

≡

The KEP Instruction Set

- Includes all kernel statements
- In addition, some derived statements
  This redundancy improves space/time efficiency

```
TOS:                    % trap T in
A0:                     %  loop
    PAUSE               %   pause;
    PRESENT S,A1        %   present S then
      EXIT TOE, TOS     %    exit T
A1:                     %   end present
    GOTO A0             %  end loop
TOE:                    % end trap;
```

≡

```
AWAIT S    % await S
```

The KEP Instruction Set

- Includes all kernel statements
- In addition, some derived statements
  This redundancy improves space/time efficiency

```
TOS:                    % trap T in
A0:                     %  loop
    PAUSE               %   pause;
    PRESENT S,A1        %   present S then
      EXIT TOE, TOS     %    exit T
A1:                     %   end present
    GOTO A0             %  end loop
TOE:                    % end trap;
```

≡

```
AWAIT S    % await S
```

- Refined ISA to reduce HW usage

  Example: `abort` can translate to

  `ABORT` in the most general case
  `LABORT` if no other `[L]ABORTS` are included in abort scope
  `TABORT` if neither `||` nor other `[L|T]ABORTS` are included

The KEP Instruction Set

- Includes all kernel statements
- In addition, some derived statements
  This redundancy improves space/time efficiency

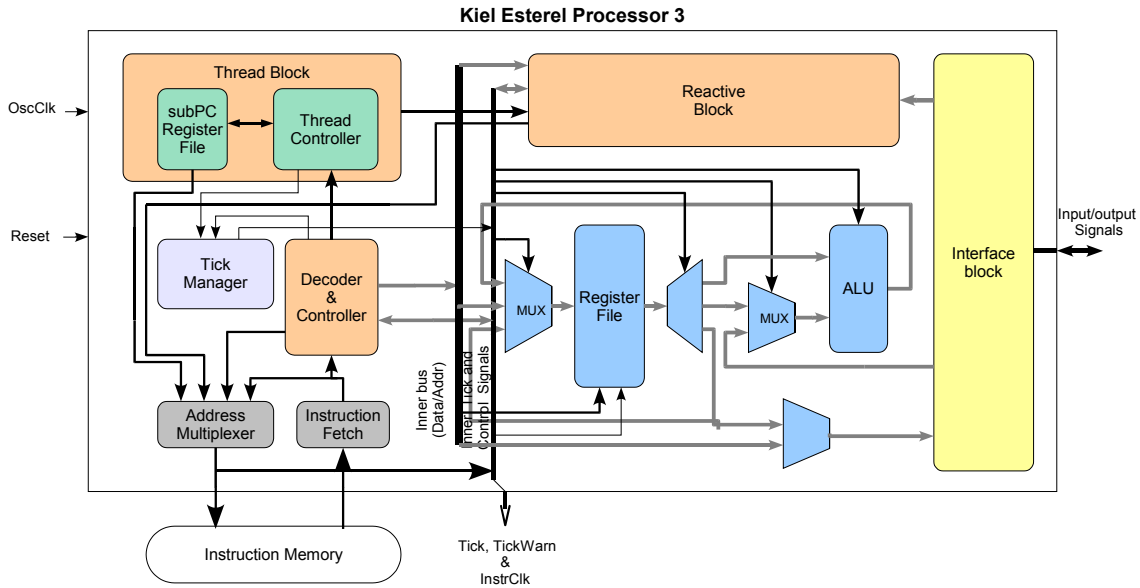
```
TOS:                    % trap T in
A0:                     %  loop
    PAUSE               %   pause;
    PRESENT S,A1        %   present S then
      EXIT TOE, TOS     %    exit T
A1:                     %   end present
    GOTO A0             %  end loop
TOE:                    % end trap;
```

≡

```
AWAIT S    % await S
```

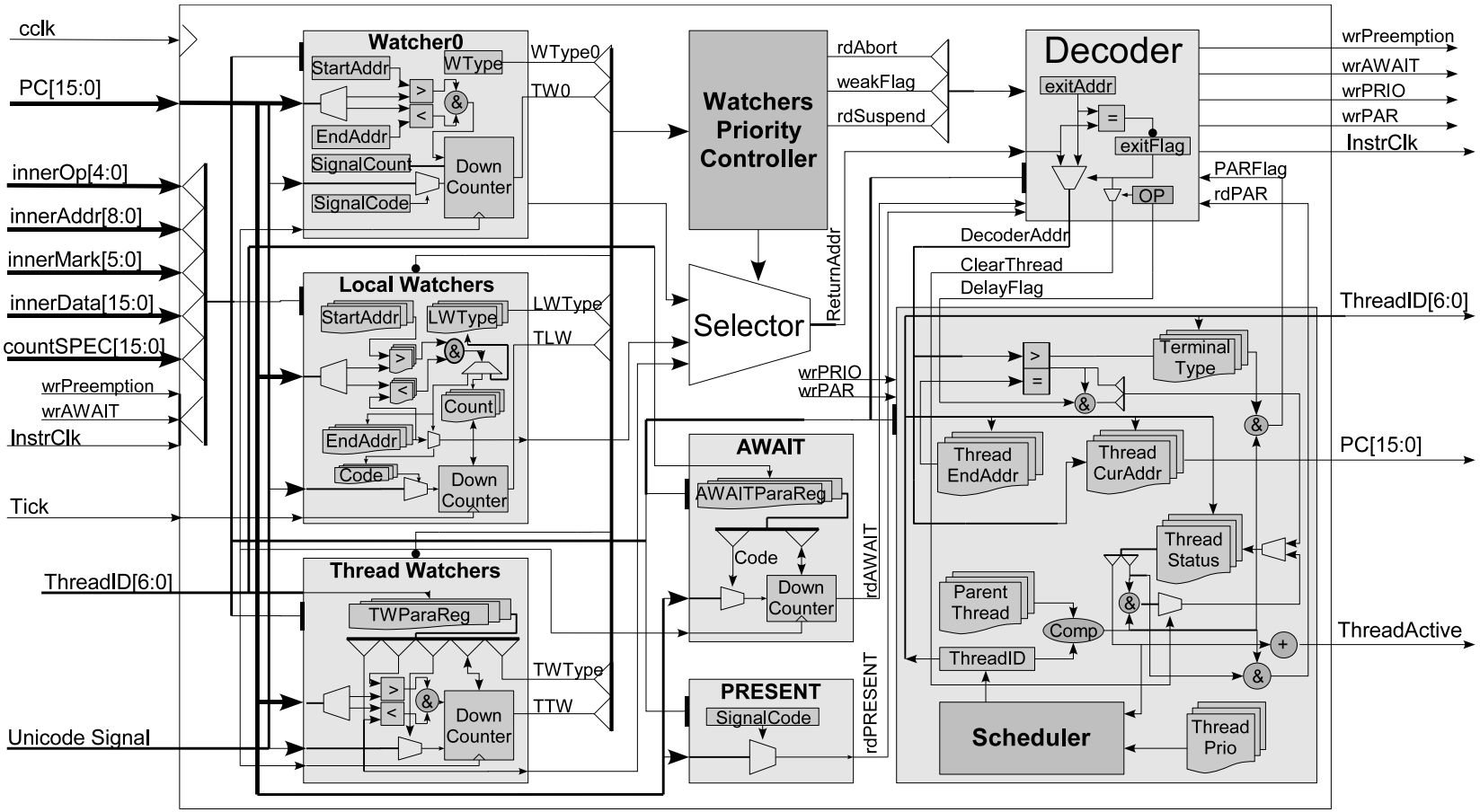
- Refined ISA to reduce HW usage
  Example: `abort` can translate to
  - `ABORT` in the most general case
  - `LABORT` if no other `[L]ABORTS` are included in abort scope
  - `TABORT` if neither `||` nor other `[L|T]ABORTS` are included
- Furthermore: valued signals, `pre`, delay expressions, ...

The Kiel Esterel Processor Architecture



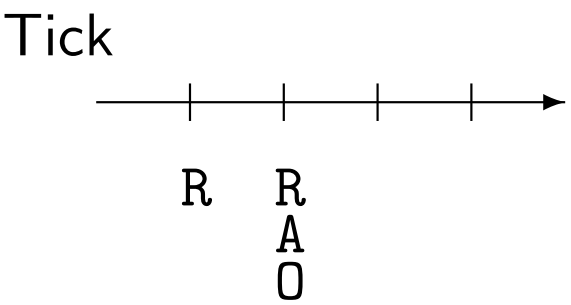
- Reactive Core
  - Decoder & Controller, Reactive Block, Thread Block
- Interface Block
  - Interface signals, Local signals, ...
- Data Handling
  - Register file, ALU, ...

The Architecture of the Reactive Core



The Compilation Challenge: Thread Dependencies

```
module Example:
output O;
signal A,R in
[
  weak abort
    sustain R;
  when immediate A;
  emit O
||
  await R;
  emit A
];
end signal
end module
```



The KEP Compiler

Thread scheduling:

1. Construct Concurrent KEP Assembler Graph (CKAG)
2. Compute thread priorities/*id*s that respect dependencies
3. Generate `PAR` and `PRIO` statements accordingly

The KEP Compiler

Thread scheduling:

1. Construct Concurrent KEP Assembler Graph (CKAG)
2. Compute thread priorities/*id*s that respect dependencies
3. Generate `PAR` and `PRIO` statements accordingly

Other tasks:

- Analyze Watcher requirements
- Map Esterel statements to KEP refined ISA

The KEP Compiler

Thread scheduling:

1. Construct Concurrent KEP Assembler Graph (CKAG)
2. Compute thread priorities/*id*s that respect dependencies
3. Generate `PAR` and `PRIO` statements accordingly

Other tasks:

- Analyze Watcher requirements
- Map Esterel statements to KEP refined ISA

Optimizations:

- Dead code elimination, based on CKAG
- "Undismantling" of kernel statements

Example Compilation

```
module Example:
output O;
signal A,R in
[
  weak abort
    sustain R;
  when immediate A;
  emit O
||
  await R;
  emit A
];
end signal
end module
```

```
sustain S
```

≡

```
loop
  emit S;
  pause;
end loop
```

```
loop
  p
end loop
```

≡

```
A:
   p;
   goto A
```

```
                % module Example
                OUTPUT O
[L00,T0]        EMIT _TICKLEN,#12
[L01,T0]        SIGNAL A
[L02,T0]        SIGNAL R
[L03,T0]        PAR 2,A0,1
[L04,T0]        PAR 1,A1,2
[L05,T0]        PARE A2,2
[L06,T1] A0:    WABORTI A,A3
[L07,T1] A4:    EMIT R
[L08,T1]          PRIO 1
[L09,T1]          PRIO 2
[L10,T1]          PAUSE
[L11,T1]        GOTO A4
[L12,T1] A3:    EMIT O
[L13,T2] A1:AWAIT R
[L14,T2]        EMIT A
[L15,T0] A2:JOIN O
[L16,T0]        HALT
```

Example—Execution Trace

Scheduling criteria: 1. active, 2. highest priority, 3. highest *id*

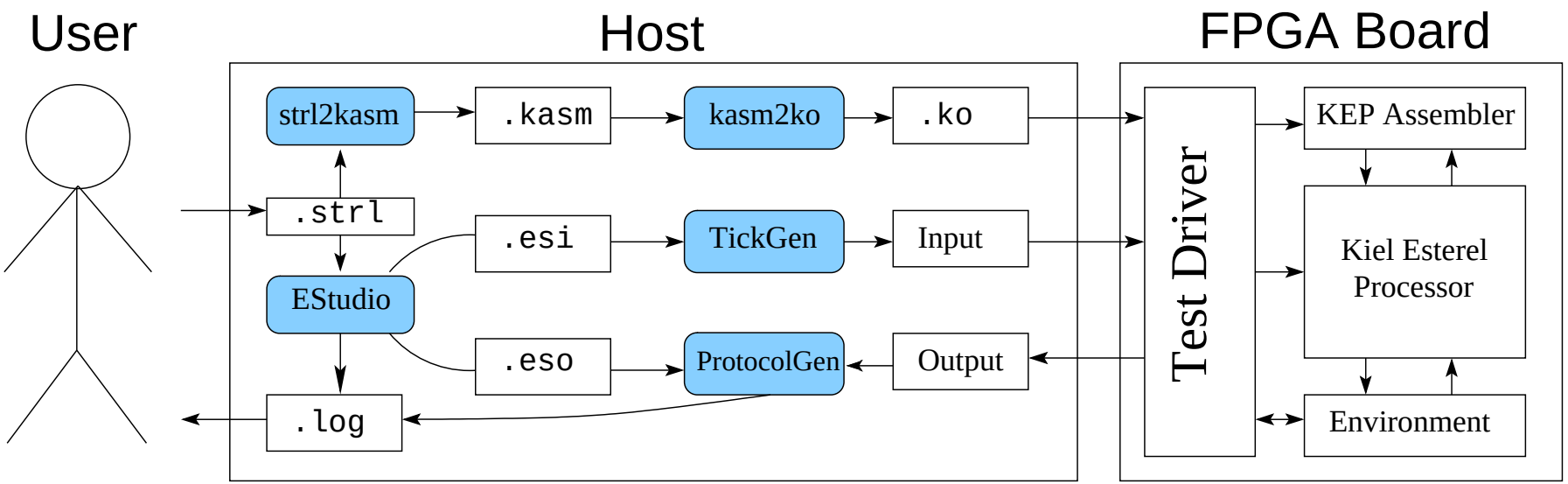
```
module Example:
output O;
signal A,R in
[
  weak abort
    sustain R;
  when immediate A;
  emit O
||
  await R;
  emit A
];
end signal
end module
```

```
                % module Example
                OUTPUT O
[L00,T0]        EMIT _TICKLEN,#12
[L01,T0]        SIGNAL A
[L02,T0]        SIGNAL R
[L03,T0]        PAR 2,A0,1
[L04,T0]        PAR 1,A1,2
[L05,T0]        PARE A2,2
[L06,T1]  A0:   WABORTI A,A3
[L07,T1]  A4:    EMIT R
[L08,T1]          PRIO 1
[L09,T1]          PRIO 2
[L10,T1]          PAUSE
[L11,T1]         GOTO A4
[L12,T1]  A3:   EMIT O
[L13,T2]  A1:AWAIT R
[L14,T2]        EMIT A
[L15,T0]  A2:JOIN 0
[L16,T0]        HALT
```

```
- Tick 1 -
! reset;
% In:
% Out: R
T0: L01, L02, L03, L04, L05
T1: L06, L07, L08
T2: L13
T1: L09, L10
T0: L15
- Tick 2 -
% In:
% Out: A R O
T1: L10, L11, L07, L08
T2: L13, L14
T1: L09, L10, L12
T0: L15, L16
- Tick 3 -
% In:
% Out:
T0: L16
```

Overview

The KEP Evaluation Platform



- Highly automated process, currently using 470+ benchmarks
- End to end validation of hardware and compiler against "trusted" reference (Esterel Studio)
- Detailed performance measurements

Performance

Memory usage

- Unoptimized: 25–94% (83% avg) reduction of memory usage (Code+RAM)
- Optimized: Yield further 5% to 30+% improvements

Speed

- WCRT speedup: typically >4x
- ACRT speedup: typically >5x
- Optimizations yield further improvements

Power

- Peak energy usage reduction: 46–84% (75% avg)
- Idle (= no inputs) energy usage reduction: 58–97% (86% avg)

The worst-/average-case reaction times comparison

Module Name	MicroBlaze						KEP3a-Unoptimized				KEP3a-optimized			
	WCRT			ACRT			WCRT	Ratio to best MB	ACRT	Ratio to best MB	WCRT	Ratio to Unopt	ACRT	Ratio to Unopt
	V5	V7	CEC	V5	V7	CEC								
abcd	1559	*954*	1476	1464	*828*	1057	135	0.14	87	0.11	135	1	84	0.97
abcdef	2281	*1462*	1714	2155	*1297*	1491	201	0.14	120	0.09	201	1	117	0.98
eight_but	3001	*1953*	2259	2833	*1730*	1931	267	0.14	159	0.09	267	1	153	0.96
chan_prot	754	*375*	623	683	*324*	435	117	0.31	60	0.19	117	1	54	0.90
reactor_ctrl	487	*230*	397	456	*214*	266	54	0.23	45	0.21	51	0.94	39	0.87
runner	566	*289*	657	512	*277*	419	36	0.12	15	0.05	30	0.83	6	0.40
example	467	*169*	439	404	*153*	228	42	0.25	24	0.16	42	1	24	1
ww_button	1185	*578*	979	1148	*570*	798	72	0.12	51	0.09	48	0.67	36	0.71
greycounter	1965	*1013*	2376	1851	*928*	1736	528	0.52	375	0.40	528	1	375	1
tcint	3580	*1878*	2350	3488	*1797*	2121	408	0.22	252	0.14	342	0.84	204	0.81
mca200	75488	29078	*12497*	73824	24056	*11479*	2862	0.23	1107	0.10	2862	1	1107	1

The worst-/average-case reaction times, in clock cycles, for the KEP3a and MicroBlaze

- WCRT speedup: typically >4x
- ACRT speedup: typically >5x
- Optimizations can yield further improvements

Memory Usage

Module Name	Esterel LOC [1]	MicroBlaze Code+Data (byte) V5 [2]	V7 (*best*)	CEC	KEP3a-Unopt. Code (word) abs. [3]	rel. [3]/[1]	Code+Data (byte) abs. [4]	rel. [4]/[2]	KEP3a-opt. Code (word) abs. [5]	rel. [5]/[3]
abcd	160	*6680*	7928	7212	168	1.05	756	0.11	164	0.93
abcdef	236	9352	9624	*9220*	252	1.07	1134	0.12	244	0.94
eight_but	312	12016	*11276*	11948	336	1.08	1512	0.13	324	0.94
chan_prot	42	3808	6204	*3364*	66	1.57	297	0.09	62	0.94
reactor_ctrl	27	2668	5504	*2460*	38	1.41	171	0.07	34	0.89
runner	31	3140	5940	*2824*	39	1.22	175	0.06	27	0.69
example	20	2480	5196	*2344*	31	1.55	139	0.06	28	0.94
ww_button	76	6112	7384	*5980*	129	1.7	580	0.10	95	0.74
greycounter	143	*7612*	7936	8688	347	2.43	1567	0.21	343	1
tcint	355	14860	*11376*	15340	437	1.23	1968	0.17	379	0.87
mca200	3090	104536	77112	*52998*	8650	2.79	39717	0.75	8650	1

- Unoptimized: 83% avg reduction of memory usage (Code+RAM)
- Optimized: May yield further 5% to 30+% improvements

Scalability

Synthesis results for Xilinx 3S1500-4fg-676[1]

Thread Count	Slices	Gates (k)
2	1295	295
10	1566	299
20	1871	311
40	2369	328
60	3235	346
80	4035	373
100	4569	389
120	5233	406

- 48 valued signals
  up to 256 possible
- 2 Watchers, 8 Local Watchers
  either up to 64 possible
- 1k (1024) instruction words
  up to 16k possible
- 128 registers (in word)
  up to 512 possible
- 16-bits (65536) max counter value
- Frequency is stable (around 60 MHz)

[1] For comparison, a MicroBlaze implementation requires around 1k slices and 309k gates; a two threads EMPEROR platform requires around 2k slices

Summary Reactive Processors

Processor supports reactive control flow directly, at hardware level

- "Watchers" monitor preemption signals
  No need for polling, interrupts
- Support for concurrency
  Multi-threading or multi-processing
- Synchronous model of computation
  Perfectly deterministic, predictable timing

Related Work/Contributions

RePIC [Roop et al.'04]/EMPEROR [Yoong et al.'06]

- Multi-processing patched reactive processor
- Three-valued signal logic + cyclic executive

Related Work/Contributions

RePIC [Roop et al.'04]/EMPEROR [Yoong et al.'06]

- Multi-processing patched reactive processor
- Three-valued signal logic + cyclic executive

Kiel Esterel Processor 1–3

- Multi-threading custom reactive processor
- Provides most Esterel primitives, but still incomplete
- No compilation scheme to support concurrency

Related Work/Contributions

RePIC [Roop et al.'04]/EMPEROR [Yoong et al.'06]

- Multi-processing patched reactive processor
- Three-valued signal logic + cyclic executive

Kiel Esterel Processor 1–3

- Multi-threading custom reactive processor
- Provides most Esterel primitives, but still incomplete
- No compilation scheme to support concurrency

KEP3a (this work)

- Provides all Esterel primitives
- Refined ISA
- Compiler exploits multi-threading

Outlook

- Improve priority assignments
- Speedup signal expression computations with external logic block
- WCRT analysis with concurrency
- Extend to Esterel v7
- KEP in Esterel—*e. g.*, to produce Esterel virtual machine
- Combination with multi-core (for data handling)
- Adaptation to non-Esterel languages

Outlook

- Improve priority assignments
- Speedup signal expression computations with external logic block
- WCRT analysis with concurrency
- Extend to Esterel v7
- KEP in Esterel—*e. g.*, to produce Esterel virtual machine
- Combination with multi-core (for data handling)
- Adaptation to non-Esterel languages

Thanks!

Questions/Comments?

Appendix

KEP3a Instruction Set + Architecture

- Esterel-Type Instructions
- Handling Concurrency
- Handling Preemption
- Handling Exceptions
- WCRT Self-Monitoring

The Compiler

- Three Compilation Steps
- The Concurrent KEP Assembler Graph
- Cyclicity
- Constraints

Further Measurements

- Code Characteristics and Compilation Times
- Speed, Size, Power, Scalability
- Analysis of context switches
- Another Example

Summary

- Multi-processing vs. Multi-threading
- Comparison of Synthesis Options
- Application Scenarios

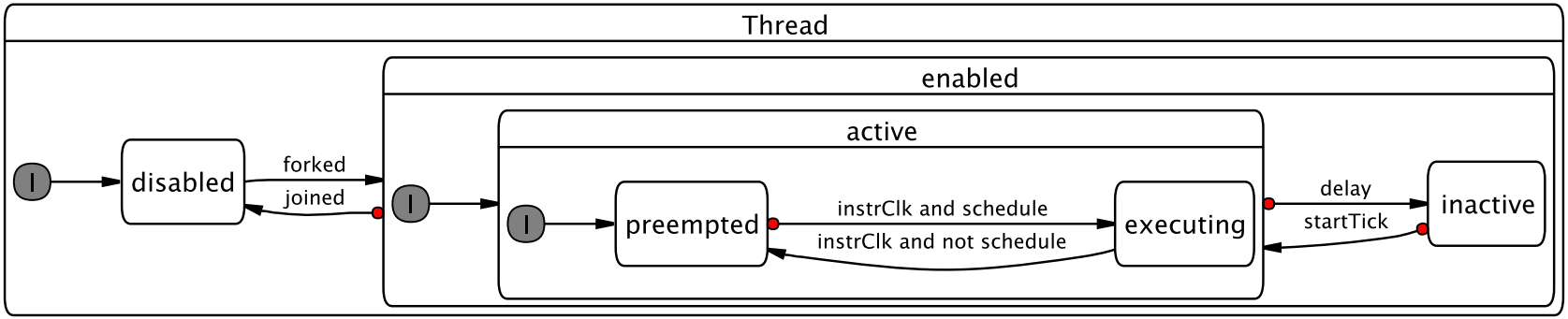
Instruction Set Summary 1/2

Mnemonic, Operands	Esterel Syntax	Notes
PAR *Prio*, *startAddr* [, *ID*] PARE *endAddr* JOIN	[*p* || *q*]	Fork and join. An optional *ID* explicitly specifies the ID of the created thread.
PRIO *Prio*		Set the priority of the current thread
[W]ABORT [*n*,] *S*, *endAddr*	[weak] abort ... when [*n*] *S*	*S* can be one of the following: 1. *S*: signal status (present/absent) 2. PRE(*S*): previous status of signal 3. TICK: always present *n* can be one of the following: 1. #*data*: immediate data 2. *reg*: register contents 3. ?*S*: value of a signal 4. PRE(?*S*): previous value of a signal
[W]ABORTI *S*, *endAddr*	[weak] abort ... when immediate *S*	
SUSPEND[I] *S*, *endAddr*	suspend ... when [immediate] *S*	
EXIT *TrapEnd*[,*TrapStart*]	trap *T* in exit *T* end trap	Exit from a trap, *TrapStart* and *TrapEnd* specify trap scope. Unlike GOTO, check for concurrent EXITs and terminate enclosing ||

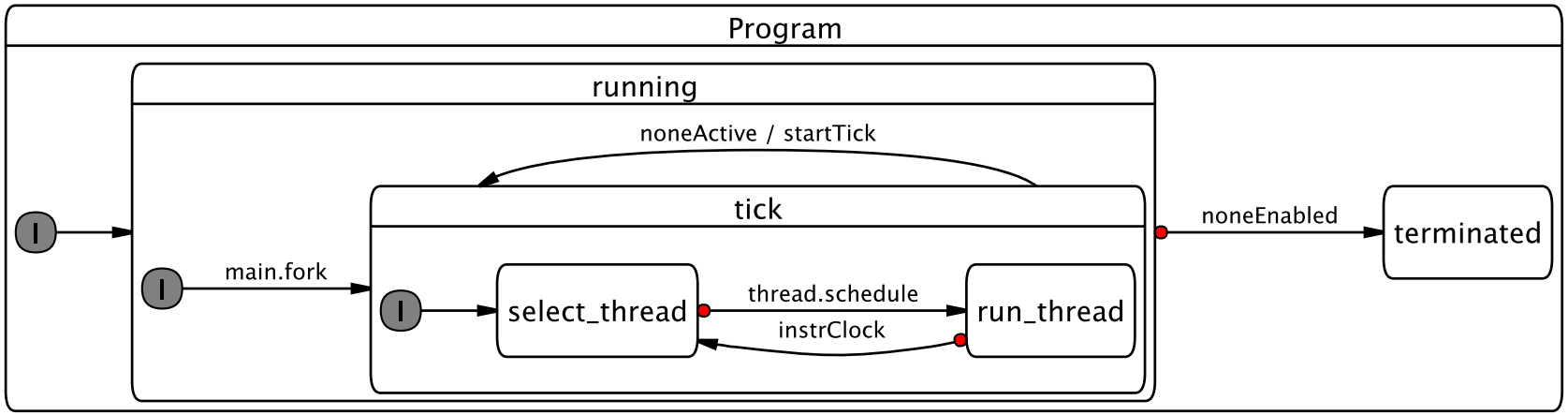
Instruction Set Summary 2/2

Mnemonic, Operands	Esterel Syntax	Notes
PAUSE	pause	Wait for a signal. AWAIT TICK is equivalent to PAUSE
AWAIT [*n*,] *S*	await [*n*] *S*	
AWAIT[I] *S*	await [immediate] *S*	
CAWAITS CAWAIT[I] S, *addr* CAWAITE	await case [immediate] *S* do end	wait for several signals in parallel
SIGNAL *S*	signal *S* in ...end	Initialize a local signal *S*
EMIT *S* [, {#*data*|*reg*}]	emit *S* [(*val*)]	Emit (valued) signal *S*
SUSTAIN *S* [, {#*data*|*reg*}]	sustain *S* [(*val*)]	Sustain (valued) signal *S*
PRESENT *S*, *elseAddr*	present *S* then ...end	Jump to *elseAddr* if *S* is absent
NOTHING	nothing	Do nothing
HALT	halt	Halt the program
GOTO *addr*	loop ...end loop	Jump to *addr*
CALL *addr* RETURN	call *P*	call a procedure, and return from the procedure

Handling Concurrency



Execution status of a single thread



The status of the whole program, as managed by the Thread Block

Handling Concurrency

A thread has its

- *thread id*
- *address range* and independent *program counter*
- *priority value*
  - assigned when a thread is created
  - dynamically changed via `PRIO` instruction
- *status flags*
  - ThreadEnable
  - ThreadActive

```
% Esterel
[
   p
  ||
   q
];
```

```
% KEP Assembler
    PAR 1,A0,1
    PAR 1,A1,2
    PARE A2
A0: p
A1: q
A2: JOIN
```

Handling Preemption

Watcher contains

Enable Watcher (EW)

- Watches the PC (Program Counter)
- Compares PC
- Preemption *enabled*?

Trigger Watcher (TW)

- Watches the Signal
- Counts down the counter (abortion)
- Preemption *active*?

```
% Esterel
abort
  weak abort
    p;
  when S2;
  q;
when S1;
```

```
% KEP Assembler
    ABORT S1,A1
    WABORT S2,A0
    p
A0: q
A1:
```

Watcher Refinement

Thread Watcher

- belongs to a thread directly
- can neither include concurrent threads nor other preemptions
- least powerful, but also cheapest

Local Watcher

- may include concurrent threads and also preemptions handled by a Thread Watcher
- cannot include another Local Watcher

Watcher

- may include concurrent threads and any preemptions
- most powerful, but also most expensive

Handling Exceptions

Exception

- has its address range
- sets an exitFlag
  - cleared when reaching the end of the trap scope
  - effects control at the join point
- can be overridden based on the corresponding trap scopes (address range)

```
% Esterel
trap T1 in
  trap T2 in
  [ p;
    exit T1;
   ||
    q;
    exit T2; ];
  end trap;
  r;
end trap;
```

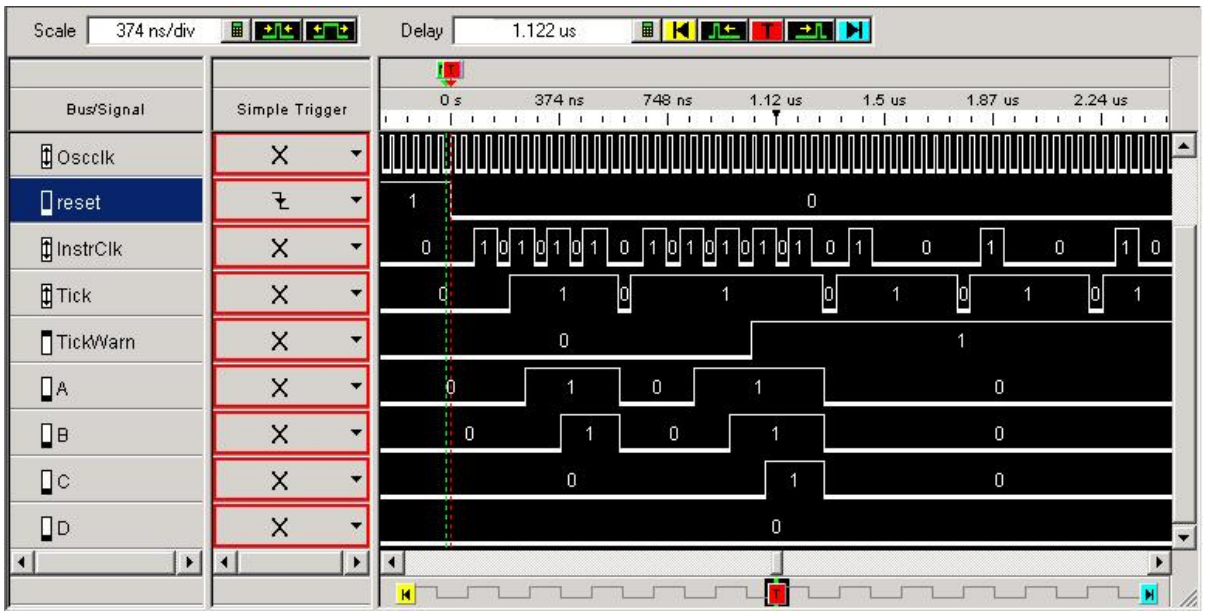
```
% KEP Assembler
T1S: T2S:
    PAR 1,A1,1
    PAR 1,A2,2
    PARE A3
A1: p
    EXIT T1,T1S
A2: q
    EXIT T2,T2E
A3: JOIN
T2E:r
T1E:
```

WCRT (Tick Length) Self-Monitoring

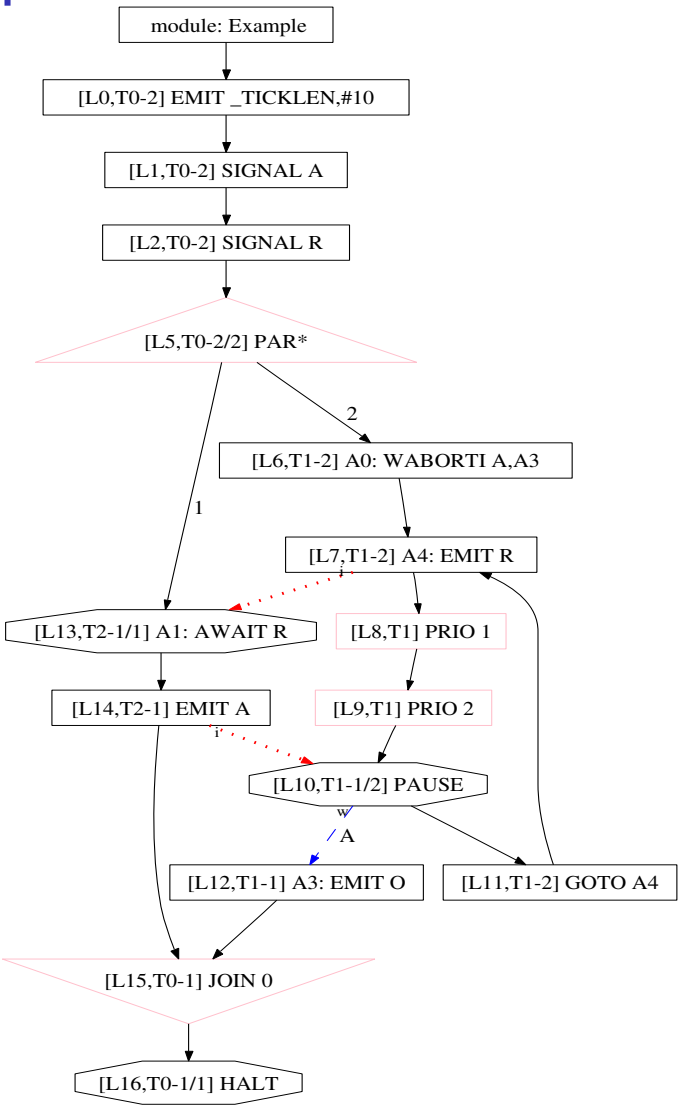
- OscClk: external clock; InstrClk: instructions; Tick: logical ticks
- Emitting special signal `_TICKLEN` configures Tick Manager with WCRT
- TickWarn pin indicates WCRT timing violation

```
% KEP Assembler
% module OVERRUN
INPUT D
OUTPUT A,B,C

EMIT _TICKLEN, #3
EMIT A
EMIT B
PAUSE
EMIT A
EMIT B
EMIT C
AWAIT D
```



Step 1: Construct Concurrent KEP Assembler Graph



⇒

```
                % module Example
                OUTPUT O
[L00,T0]        EMIT _TICKLEN,#12
[L01,T0]        SIGNAL A
[L02,T0]        SIGNAL R
[L03,T0]        PAR 2,A0,1
[L04,T0]        PAR 1,A1,2
[L05,T0]        PARE A2,2
[L06,T1]  A0:   WABORTI A,A3
[L07,T1]  A4:    EMIT R
[L08,T1]          PRIO 1
[L09,T1]          PRIO 2
[L10,T1]          PAUSE
[L11,T1]         GOTO A4
[L12,T1]  A3:   EMIT O
[L13,T2]  A1:  AWAIT R
[L14,T2]        EMIT A
[L15,T0]  A2:  JOIN 0
[L16,T0]       HALT
```

Step 2: Compute Thread Priorities/*ids*

- Compute priority for current tick at each node
- Compute priority for next tick at tick boundaries

Step 2: Compute Thread Priorities/*ids*

- Compute priority for current tick at each node
- Compute priority for next tick at tick boundaries
- Priority within tick must not increase
- Initialize tick boundaries with lowest priority, compute priorites backwards

Step 2: Compute Thread Priorities/*ids*

- Compute priority for current tick at each node
- Compute priority for next tick at tick boundaries
- Priority within tick must not increase
- Initialize tick boundaries with lowest priority, compute priorites backwards
- Judicious traversal of CKAG allows to compute each priority just once
  - Facilitates correctness argument
  - Complexity linear in CKAG size

Step 3: Generate PAR/PRIO Statements

- Enforce that a statement is always executed with same priority, irrespective of control flow
- Must consider priorities for current and for next tick
- Again linear complexity

CKAG Node Types

The CKAG distinguishes the following sets of nodes:

D: Delay nodes (octagons)

- `PAUSE`, `AWAIT`, `HALT`, `SUSTAIN`

F: Fork nodes (triangles)

- `PAR`/`PARE`

T: Transient nodes (rectangles/inverted triangles)

- `EMIT`, `PRESENT`, etc. (rectangles)
- `JOIN` nodes (inverted triangles)

N: Set of all nodes, $N = D \cup F \cup T$

The Concurrent KEP Assembler Graph (CKAG)

Define

- for each fork node n:
  - **n.join**: the `JOIN` statement corresponding to n,
  - **n.sub**: the transitive closure of nodes in threads generated by n.
- for abort nodes n (`[L|T][W]ABORT[I]`, `SUSPEND[I]`):
  - **n.end**: the end of the abort scope opened by n,
  - **n.scope**: the nodes within n's abort scope.
- for all nodes n:
  - **n.prio**: the priority that the thread executing n should be running with
- for $n \in D \cup F$,
  - **n.prionext**: the priority that the thread executing n should be resumed with in the subsequent tick.

CKAG Dependency Types

Define dependencies

$n.dep_i$: the dependency sinks with respect to *n* at the current tick (the *immediate dependencies*)

$n.dep_d$: the dependency sinks with respect to *n* at the next tick (the *delayed dependencies*)
Induced by emissions of strong abort trigger signals and corresponding delay nodes within the abort scope

CKAG Successor Types

Define following types of successors for each n:

$n.suc_c$: the *control successors*.

$n.suc_w$: the *weak abort successors*

$n.suc_s$: the *strong abort successors*

$n.suc_f$: the *flow successors*
the set $n.suc_c \cup n.suc_w \cup n.suc_s$

For $n \in F$ we also define the following *fork abort successors*

$n.suc_{wf}$: the *weak fork abort successors*

$n.suc_{sf}$: the *strong fork abort successors*

Program Cycle

An Esterel program is considered cyclic iff the corresponding CKAG contains a path from a node to itself, where for all nodes n and their successors along that path, n' and n'', the following holds:

$$
\begin{aligned}
& n \in D \wedge n' \in n.suc_w \\
\vee\ & n \in F \wedge n' \in n.suc_c \cup n.suc_{wf} \\
\vee\ & n \in T \wedge n' \in n.suc_c \cup n.dep_i \\
\vee\ & n \in T \wedge n' \in n.dep_d \wedge n'' \in n'.suc_c \cup n'.suc_s \cup n'.suc_{sf}\,.
\end{aligned}
$$

Constraints

A correct priority assignment must fulfill the following constraints, where m, n are arbitrary nodes in the CKAG

Constraint (Dependencies)

- *For* $m \in n.dep_i$*:* $n.prio > m.prio$
- *For* $m \in n.dep_d$*:* $n.prio > m.prionext$

Constraint (Intra-Tick Priority)

- *For* $n \in D$ *and* $m \in n.suc_w$*, or* $n \in F$ *and* $m \in n.suc_c \cup n.suc_{wf}$*, or* $n \in T$ *and* $m \in n.suc_c$*:* $n.prio \geq m.prio$

Computing Thread Priorities

Constraint (Inter-Tick Priority for Delay Nodes)

- *For all* $m \in n.suc_c \cup n.suc_s$*:* $n.prionext \geq m.prio$

Constraint (Inter-Tick Priority for Fork Nodes)

- $n.prionext \geq n.join.prio$
- *For all* $m \in n.suc_{sf}$*:* $n.prionext \geq m.prio$

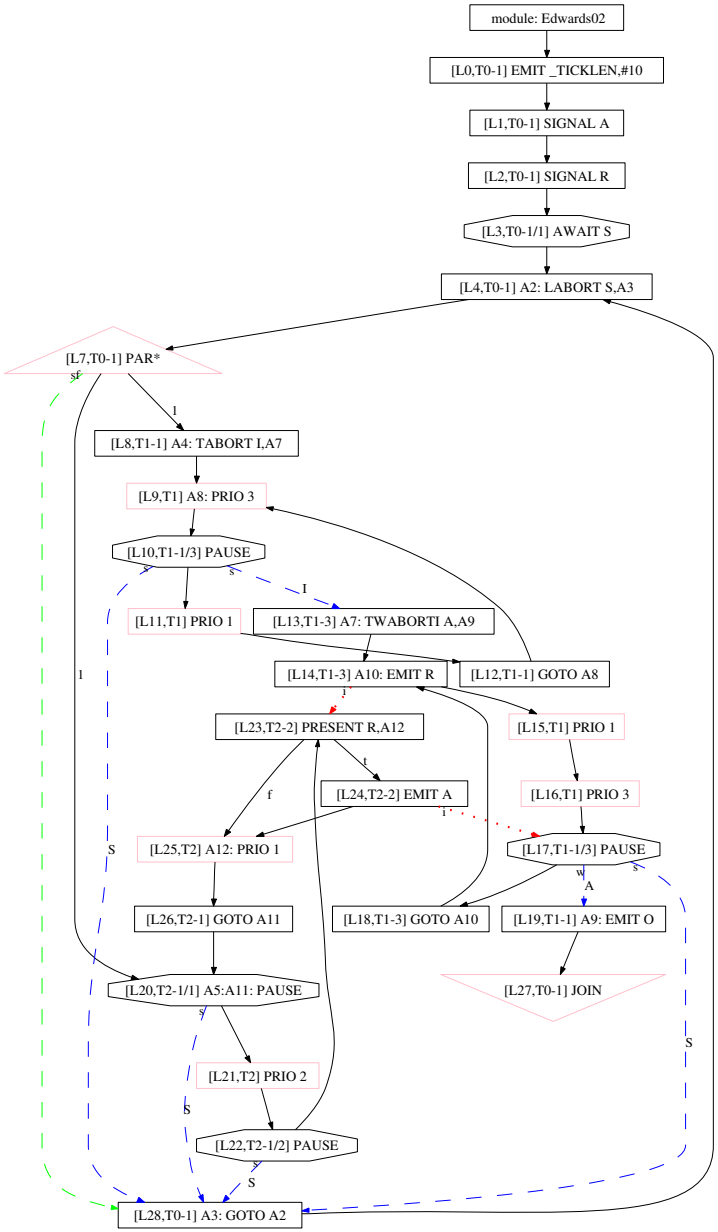
Computing Thread Priorities

```
module Edwards02:
input S, I;
output O;

signal A,R in
  every S do
    await I;
    weak abort
      sustain R;
    when immediate A;
    emit O;
  ||
    loop
      pause;
      pause;
      present R then
        emit A;
      end present
    end loop
  end every
end signal
end module
```

```
module Edwards02-dism:
input S,I;
output O;
signal A, R in
  abort
    loop
      pause
    end loop
  when S;
  loop
    abort
      [ abort
          loop
            pause
          end loop
        when I;
        weak abort
          loop
            emit R;
            pause
          end loop
        when immediate A;
        emit O
      ||
        % cont...
```

```
        % cont...
      ||
        loop
          pause;
          pause;
          present R then
            emit A
          end present
        end loop ];
      loop
        pause
      end loop
    when S
  end loop
end signal
end module
```



⇒

```
                INPUT S,I
                OUTPUT O
[L00,T0]        EMIT _TICKLEN,#20
[L01,T0]        SIGNAL A
[L02,T0]        SIGNAL R
[L03,T0]        AWAIT S
[L04,T0] A2:    LABORT S,A3
[L05,T0]        PAR 1,A4,1
[L06,T0]        PAR 1,A5,2
[L07,T0]        PARE A6,1
[L08,T1] A4:    TABORT I,A7
[L09,T1] A8:    PRIO 3
[L10,T1]        PAUSE
[L11,T1]        PRIO 1
[L12,T1]        GOTO A8
[L13,T1] A7:    TWABORTI A,A9
[L14,T1] A10:EMIT R
[L15,T1]        PRIO 1
[L16,T1]        PRIO 3
[L17,T1]        PAUSE
[L18,T1]        GOTO A10
[L19,T1] A9:    EMIT O
[L20,T2] A5:A11: PAUSE
[L21,T2]        PRIO 2
[L22,T2]        PAUSE
[L23,T2]        PRESENT R,A12
[L24,T2]        EMIT A
[L25,T2] A12:PRIO 1
[L26,T2]        GOTO A11
[L27,T0] A6:    JOIN
[L28,T0] A3:    GOTO A2
```

Optimized Priority Assignment

```
                INPUT S,I
                OUTPUT O
  [L00,T0]      EMIT _TICKLEN,#20
  [L01,T0]      SIGNAL A
  [L02,T0]      SIGNAL R
  [L03,T0]      AWAIT S
  [L04,T0]  A2: LABORT S,A3
  [L05,T0]      PAR 1,A4,1
  [L06,T0]      PAR 1,A5,2
  [L07,T0]      PARE A6,1
  [L08,T1]  A4: TABORT I,A7
  [L09,T1]  A8: PRIO 3
  [L10,T1]      PAUSE
  [L11,T1]      PRIO 1
  [L12,T1]      GOTO A8
  [L13,T1]  A7: TWABORTI A,A9
  [L14,T1]  A10:EMIT R
  [L15,T1]      PRIO 1
  [L16,T1]      PRIO 3
  [L17,T1]      PAUSE
  [L18,T1]      GOTO A10
  [L19,T1]  A9: EMIT O
  [L20,T2]  A5:A11: PAUSE
  [L21,T2]      PRIO 2
  [L22,T2]      PAUSE
  [L23,T2]      PRESENT R,A12
  [L24,T2]      EMIT A
  [L25,T2]  A12:PRIO 1
  [L26,T2]      GOTO A11
  [L27,T0]  A6: JOIN
  [L28,T0]  A3: GOTO A2
```

$\Rightarrow$

```
                INPUT S,I
                OUTPUT O
  [L00,T0]      EMIT _TICKLEN,#20
  [L01,T0]      SIGNAL A
  [L02,T0]      SIGNAL R
  [L03,T0]      AWAIT S
  [L04,T0]  A2: LABORT S,A3
  [L05,T0]      PAR 3,A4,1
  [L06,T0]      PAR 2,A5,2
  [L07,T0]      PARE A6,1
  [L08,T1]  A4: AWAIT I
  [L09,T1]  A7: TWABORTI A,A9
  [L10,T1]  A10:EMIT R
  [L11,T1]      PRIO 1
  [L12,T1]      PRIO 3
  [L13,T1]      PAUSE
  [L14,T1]      GOTO A10
  [L15,T1]  A9: EMIT O
  [L16,T2]  A5:A11: PAUSE
  [L17,T2]      PAUSE
  [L18,T2]      PRESENT R,A12
  [L19,T2]      EMIT A
  [L20,T2]  A12:GOTO A11
  [L21,T0]  A6: JOIN
  [L22,T0]  A3: GOTO A2
```

Code Characteristics and Compilation Times

Module Name	Esterel					KEP3a (Unoptimized|optimized)								MicroBlaze Compiling Time (Sec) (V5/V7/CEC)
	Threads			Preemptions		CKAG				Preemption handled by			Compiling Time (Sec)	
	Cnt	Max Depth	Max Conc	Cnt	Max Depth	Nodes	Dep. Num	Max Priority	PRIO Instr	Watcher	Local Watcher	Thread Watcher		
abcd	4	2	4	20	2	211	36	3	30	0	4|3	16|11	0.15	0.12 0.09 0.30
abcdef	6	2	6	30	2	313	90	3	48	0	6|5	24|17	0.21	0.71 0.46 0.96
eight_but	8	2	8	40	2	415	168	3	66	0	8|7	32|23	0.26	0.99 0.54 1.25
chan_prot	5	3	4	6	1	80	4	2	10	0	0	6|4	0.07	0.35 0.35 0.43
reactor_ctrl	3	2	3	5	1	51	5	1	0	0	1|0	4	0.06	0.29 0.31 0.36
runner	2	2	2	9	3	61	0	1	0	3|2	1	5|3	0.05	0.30 0.34 0.40
example	2	2	2	4	2	36	2	3	6	0	1	3|2	0.05	0.28 0.31 0.31
ww_button	13	3	4	27	2	194	0	1	0	0	5	22|10	0.10	0.44 0.40 0.64
greycounter	17	3	13	19	2	414	53	6	58	0	4	15	0.34	0.57 0.43 0.75
tcint	39	5	17	18	2	583	65	3	20	0	1	17|10	0.34	0.41 0.52 1.11
mca200	59	5	49	64	4	11219	129	11	190	2	14	48	11.25	69.81 12.99 7.37

Note: In the mca200, the watcher refinement reduces the hardware requirements from 4033 slices (if all preemptions were handled by general purpose Watchers) to 3265 slices (19% reduction).

Worst-/Average-Case Reaction Times

Module Name	MicroBlaze						KEP3a-Unoptimized				KEP3a-optimized			
	WCRT			ACRT			WCRT	Ratio to best MB	ACRT	Ratio to best MB	WCRT	Ratio to Unopt	ACRT	Ratio to Unopt
	V5	V7	CEC	V5	V7	CEC								
abcd	1559	*954*	1476	1464	*828*	1057	135	0.14	87	0.11	135	1	84	0.97
abcdef	2281	*1462*	1714	2155	*1297*	1491	201	0.14	120	0.09	201	1	117	0.98
eight_but	3001	*1953*	2259	2833	*1730*	1931	267	0.14	159	0.09	267	1	153	0.96
chan_prot	754	*375*	623	683	*324*	435	117	0.31	60	0.19	117	1	54	0.90
reactor_ctrl	487	*230*	397	456	*214*	266	54	0.23	45	0.21	51	0.94	39	0.87
runner	566	*289*	657	512	*277*	419	36	0.12	15	0.05	30	0.83	6	0.40
example	467	*169*	439	404	*153*	228	42	0.25	24	0.16	42	1	24	1
ww_button	1185	*578*	979	1148	*570*	798	72	0.12	51	0.09	48	0.67	36	0.71
greycounter	1965	*1013*	2376	1851	*928*	1736	528	0.52	375	0.40	528	1	375	1
tcint	3580	*1878*	2350	3488	*1797*	2121	408	0.22	252	0.14	342	0.84	204	0.81
mca200	75488	29078	*12497*	73824	24056	*11479*	2862	0.23	1107	0.10	2862	1	1107	1

The worst-/average-case reaction times, in clock cycles, for the KEP3a and MicroBlaze

- WCRT speedup: typically >4x
- ACRT speedup: typically >5x
- Optimizations yield further improvements

Memory Usage

Module Name	Esterel LOC [1]	MicroBlaze Code+Data (byte) V5 [2]	V7 (*best*) [2]	CEC [2]	KEP3a-Unopt. Code (word) abs. [3]	rel. [3]/[1]	Code+Data (byte) abs. [4]	rel. [4]/[2]	KEP3a-opt. Code (word) abs. [5]	rel. [5]/[3]
abcd	160	*6680*	7928	7212	168	1.05	756	0.11	164	0.93
abcdef	236	9352	9624	*9220*	252	1.07	1134	0.12	244	0.94
eight_but	312	12016	*11276*	11948	336	1.08	1512	0.13	324	0.94
chan_prot	42	3808	6204	*3364*	66	1.57	297	0.09	62	0.94
reactor_ctrl	27	2668	5504	*2460*	38	1.41	171	0.07	34	0.89
runner	31	3140	5940	*2824*	39	1.22	175	0.06	27	0.69
example	20	2480	5196	*2344*	31	1.55	139	0.06	28	0.94
ww_button	76	6112	7384	*5980*	129	1.7	580	0.10	95	0.74
greycounter	143	*7612*	7936	8688	347	2.43	1567	0.21	343	1
tcint	355	14860	*11376*	15340	437	1.23	1968	0.17	379	0.87
mca200	3090	104536	77112	*52998*	8650	2.79	39717	0.75	8650	1

- Unoptimized: 83% avg reduction of memory usage (Code+RAM)
- Optimized: May yield further 5% to 30+% improvements

Power Consumption

Module Name	MicroBlaze (82mW@50MHz)	KEP3a [2] (mW)		Ratio (KEP to MB)	
	Idle	Peak	Idle	Peak	Idle
abcd	69	13	8	0.16	0.12
abcdef	74	13	7	0.16	0.09
eight_but	74	13	7	0.16	0.09
chan_prot	70	28	12	0.34	0.17
reactor_ctrl	76	20	13	0.24	0.17
runner	78	14	2	0.17	0.03
example	77	25	9	0.30	0.12
ww_button	81	13	4	0.16	0.05
greycounter	78	44	33	0.54	0.42
tcint	80	18	10	0.22	0.13

- Peak energy usage reduction: 75% avg
- Idle (= no inputs) energy usage reduction: 86% avg

[2] Based on Xilinx 3S200-4ft256, requires an additional 37mW as quiescent power for the chip itself

Scalability

Synthesis results for Xilinx 3S1500-4fg-676[3]

Thread Count	Slices	Gates (k)
2	1295	295
10	1566	299
20	1871	311
40	2369	328
60	3235	346
80	4035	373
100	4569	389
120	5233	406

- 48 valued signals
  up to 256 possible
- 2 Watchers, 8 Local Watchers
  either up to 64 possible
- 1k (1024) instruction words
  up to 64k possible
- 128 registers (in word)
  up to 512 possible
- 16-bits (65536) max counter value
- Frequency is stable (around 60 MHz)

Note: In the `mca200`, the watcher refinement reduces the hardware requirements from 4033 slices (if all preemptions were handled by general purpose `Watchers`) to 3265 slices (19% reduction).

[3] For comparison, a MicroBlaze implementation requires around 1k slices

Analysis of Context Switches

Module Name	Instr's total abs. [1]	CSs total abs. [2]	CSs total ratio [1]/[2]	CSs at same priority abs. [3]	CSs at same priority rel. [3]/[2]	PRIOs total abs. [4]	PRIOs total rel. [4]/[1]	CSs due to PRIO abs. [5]	CSs due to PRIO rel. [5]/[2]	CSs due to PRIO rel. [5]/[4]
abcd	16513	3787	4.36	1521	0.40	3082	0.19	1243	0.33	0.40
abcdef	29531	7246	4.08	3302	0.46	6043	0.20	2519	0.35	0.42
eight_but	39048	10073	3.88	5356	0.53	8292	0.21	3698	0.37	0.45
chan_prot	5119	1740	2.94	707	0.41	990	0.19	438	0.25	0.44
reactor_ctrl	151	48	3.15	29	0.60	0	0	0	0	-
runner	5052	704	7.18	307	0.44	0	0	0	0	-
example	208	60	3.47	2	0.30	26	0.13	9	0.15	0.35
ww_button	292	156	1.87	92	0.59	0	0	0	0	-
greycounter	160052	34560	4.63	14043	0.41	26507	0.17	12725	0.37	0.48
tcint	80689	33610	2.4	16769	0.50	5116	0.06	2129	0.06	0.42
mca200	982417	256988	3.82	125055	0.49	242457	0.25	105258	0.41	0.43

Edwards02: Esterel to KEP

```
module Edwards02:
input S, I;
output O;

signal A,R in
  every S do
    await I;
    weak abort
      sustain R;
    when immediate A;
    emit O;
  ||
    loop
      pause;
      pause;
      present R then
        emit A;
      end present
    end loop
  end every
end signal
end module
```

```
every S do
  p
end
```
≡
```
await S;
loop
  abort
    p;
    halt
  when S
end loop
```

```
sustain S
```
≡
```
loop
  emit S;
  pause;
end loop
```

```
loop
  p
end loop
```
≡
```
A:
   p;
   goto A
```

```
                INPUT S,I
                OUTPUT O
  [L00,T0]      EMIT _TICKLEN,#20
  [L01,T0]      SIGNAL A
  [L02,T0]      SIGNAL R
  [L03,T0]      AWAIT S
  [L04,T0]  A2: LABORT S,A3
  [L05,T0]      PAR 1,A4,1
  [L06,T0]      PAR 1,A5,2
  [L07,T0]      PARE A6,1
  [L08,T1]  A4: TABORT I,A7
  [L09,T1]  A8: PRIO 3
  [L10,T1]      PAUSE
  [L11,T1]      PRIO 1
  [L12,T1]      GOTO A8
  [L13,T1]  A7: TWABORTI A,A9
  [L14,T1]  A10:EMIT R
  [L15,T1]      PRIO 1
  [L16,T1]      PRIO 3
  [L17,T1]      PAUSE
  [L18,T1]      GOTO A10
  [L19,T1]  A9: EMIT O
  [L20,T2]  A5:A11: PAUSE
  [L21,T2]      PRIO 2
  [L22,T2]      PAUSE
  [L23,T2]      PRESENT R,A12
  [L24,T2]      EMIT A
  [L25,T2]  A12:PRIO 1
  [L26,T2]      GOTO A11
  [L27,T0]  A6: JOIN
  [L28,T0]  A3: GOTO A2
```

Edwards02: a Possible Execution Trace

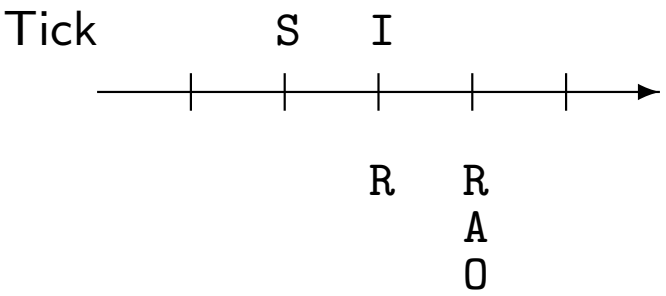
```
module Edwards02:
input S, I;
output O;

signal A,R in
  every S do
    await I;
    weak abort
      sustain R;
    when immediate A;
    emit O;
  ||
    loop
      pause;
      pause;
      present R then
        emit A;
      end present
    end loop
  end every
end signal
end module
```

```
every S do
  p
end
```
≡
```
await S;
loop
  abort
    p;
    halt
  when S
end loop
```

```
sustain S
```
≡
```
loop
  emit S;
  pause;
end loop
```

```
loop
  p
end loop
```
≡
```
A:
   p;
   goto A
```



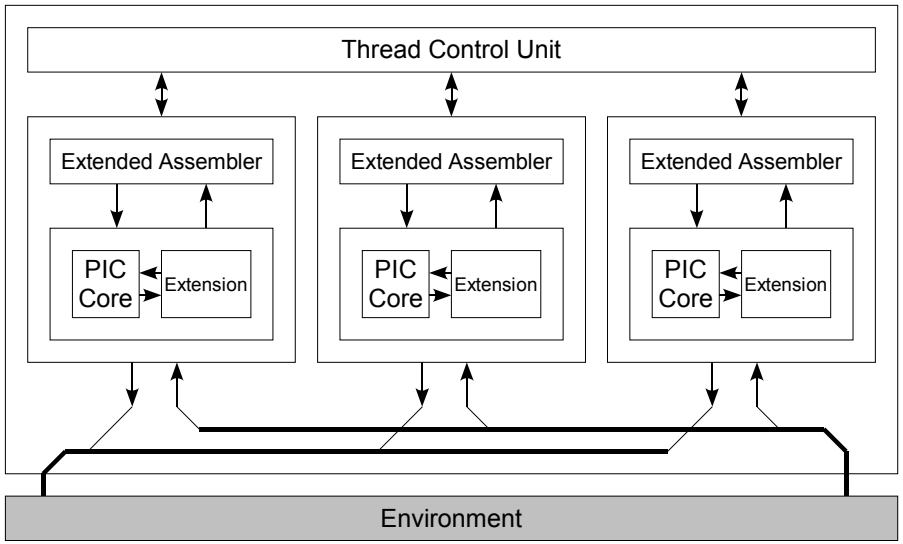
```
module Edwards02:
input S, I;
output O;

signal A,R in
  every S do
    await I;
    weak abort
      sustain R;
    when immediate A;
    emit O;
  ||
    loop
      pause;
      pause;
      present R then
        emit A;
      end present
    end loop
  end every
end signal
end module
```

```
                INPUT S,I
                OUTPUT O
   [L00,T0]     EMIT _TICKLEN,#20
   [L01,T0]     SIGNAL A
   [L02,T0]     SIGNAL R
   [L03,T0]     AWAIT S
   [L04,T0] A2: LABORT S,A3
   [L05,T0]     PAR 1,A4,1
   [L06,T0]     PAR 1,A5,2
   [L07,T0]     PARE A6,1
   [L08,T1] A4: TABORT I,A7
   [L09,T1] A8: PRIO 3
   [L10,T1]     PAUSE
   [L11,T1]     PRIO 1
   [L12,T1]     GOTO A8
   [L13,T1] A7: TWABORTI A,A9
   [L14,T1] A10:EMIT R
   [L15,T1]     PRIO 1
   [L16,T1]     PRIO 3
   [L17,T1]     PAUSE
   [L18,T1]     GOTO A10
   [L19,T1] A9: EMIT O
   [L20,T2] A5:A11: PAUSE
   [L21,T2]     PRIO 2
   [L22,T2]     PAUSE
   [L23,T2]     PRESENT R,A12
   [L24,T2]     EMIT A
   [L25,T2] A12:PRIO 1
   [L26,T2]     GOTO A11
   [L27,T0] A6: JOIN
   [L28,T0] A3: GOTO A2
```

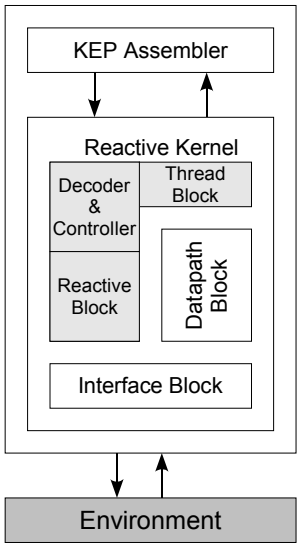
```
- Tick 1 -
! reset;
% In:
% Out:
[L01,T0] [L02,T0] [L03,T0]
- Tick 2 -
% In: S
% Out:
[L03,T0] [L04,T0] [L05,T0]
[L06,T0] [L07,T0]
[L20,T2] [L08,T1]
[L09,T1] [L10,T1]
[L27,T0]
- Tick 3 -
% In: I
% Out: R
[L10,T1] [L13,T1]
[L14,T1] [L15,T1]
[L20,T2] [L21,T2] [L22,T2]
[L16,T1] [L17,T1] [L27,T0]
- Tick 4 -
% In:
% Out: A R O
[L17,T1] [L18,T1]
[L14,T1] [L15,T1]
[L22,T2] [L23,T2] [L24,T2]
[L25,T2] [L26,T2] [L20,T2]
[L16,T1] [L17,T1] [L19,T1]
[L27,T0]
```

Multi-processing vs. Multi-threading



Multi-processing (EMPEROR/RePIC)

- Esterel thread ≈ one independent RePIC processor
- Thread Control Unit handles the synchronization and communication
- Three-valued signal representation
- `sync` command to synchronize threads



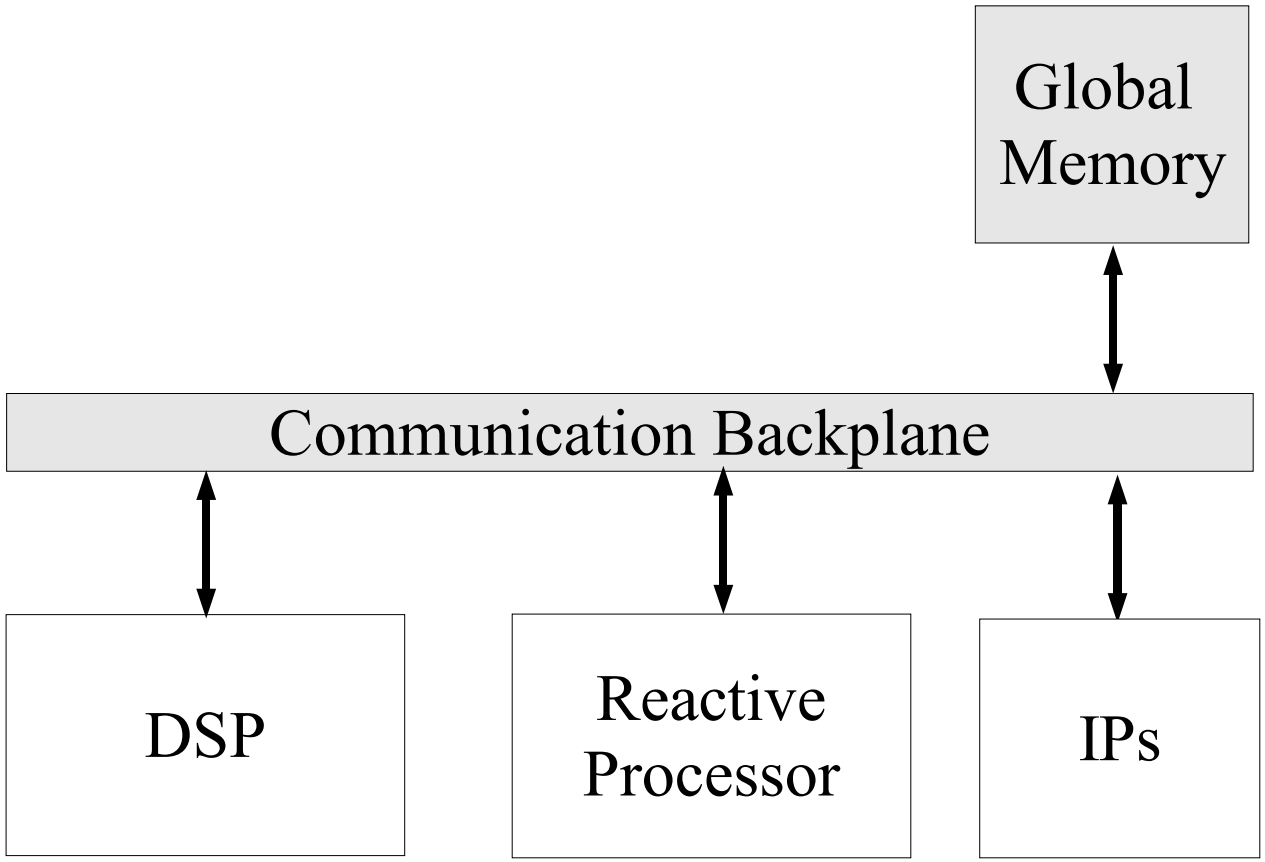
Multi-threading (KEP)

- Esterel thread ≈ several registers
- priority-based scheduler
- `PRIO` command to synchronize threads

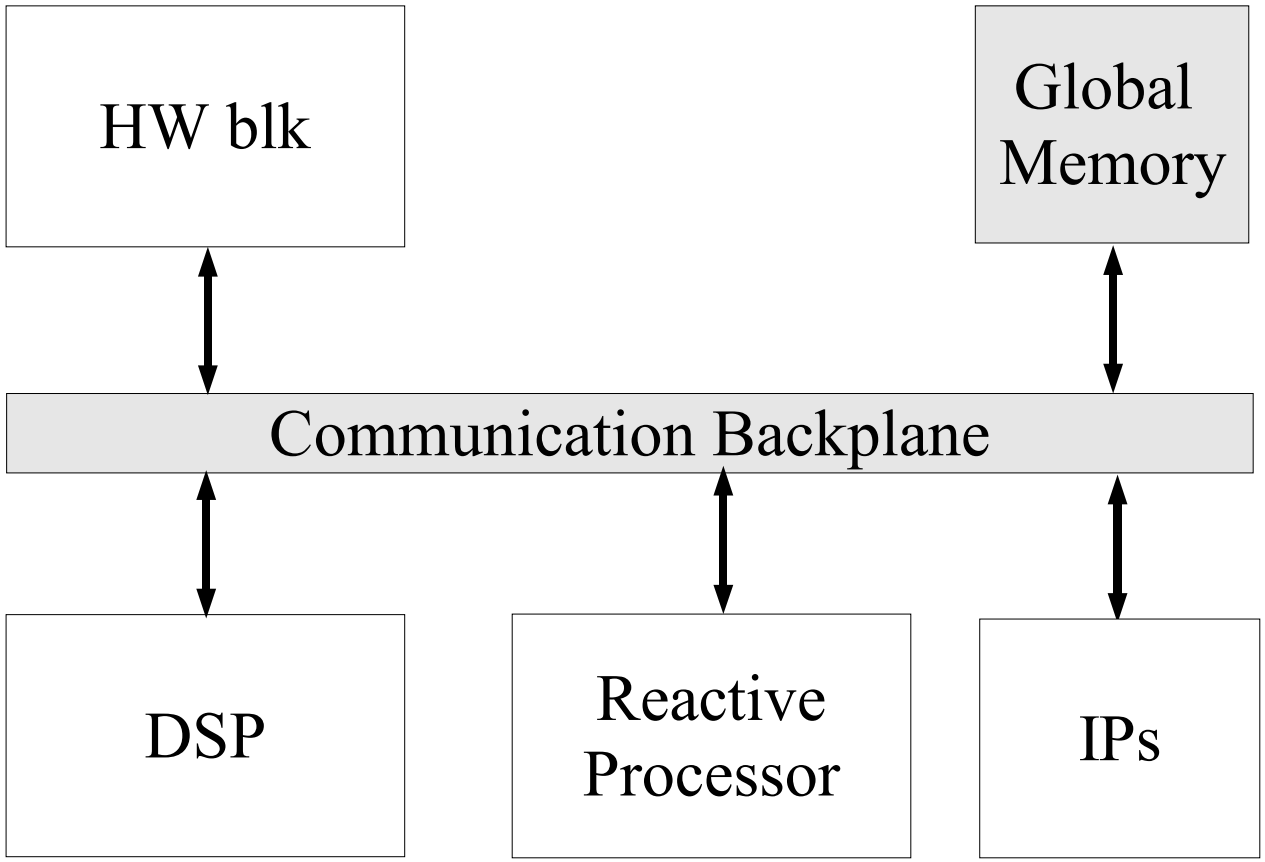
Comparison of Synthesis Options

		HW	SW	Co-design	Reactive Processor	
					Multi-processing	Multi-threading
Speed		++	−	+	+	+
Flexibility		− −	++	−	+/−	+
Scalability		+	++	+	− −	+
Cost	Logic Area	++/−	+	+	− −	+/−
	Memory	++	− −	−	+	+
	Power Usage	++	−	−	− −	+
Appl. Design Cycle		− −	++	+/−	++	++

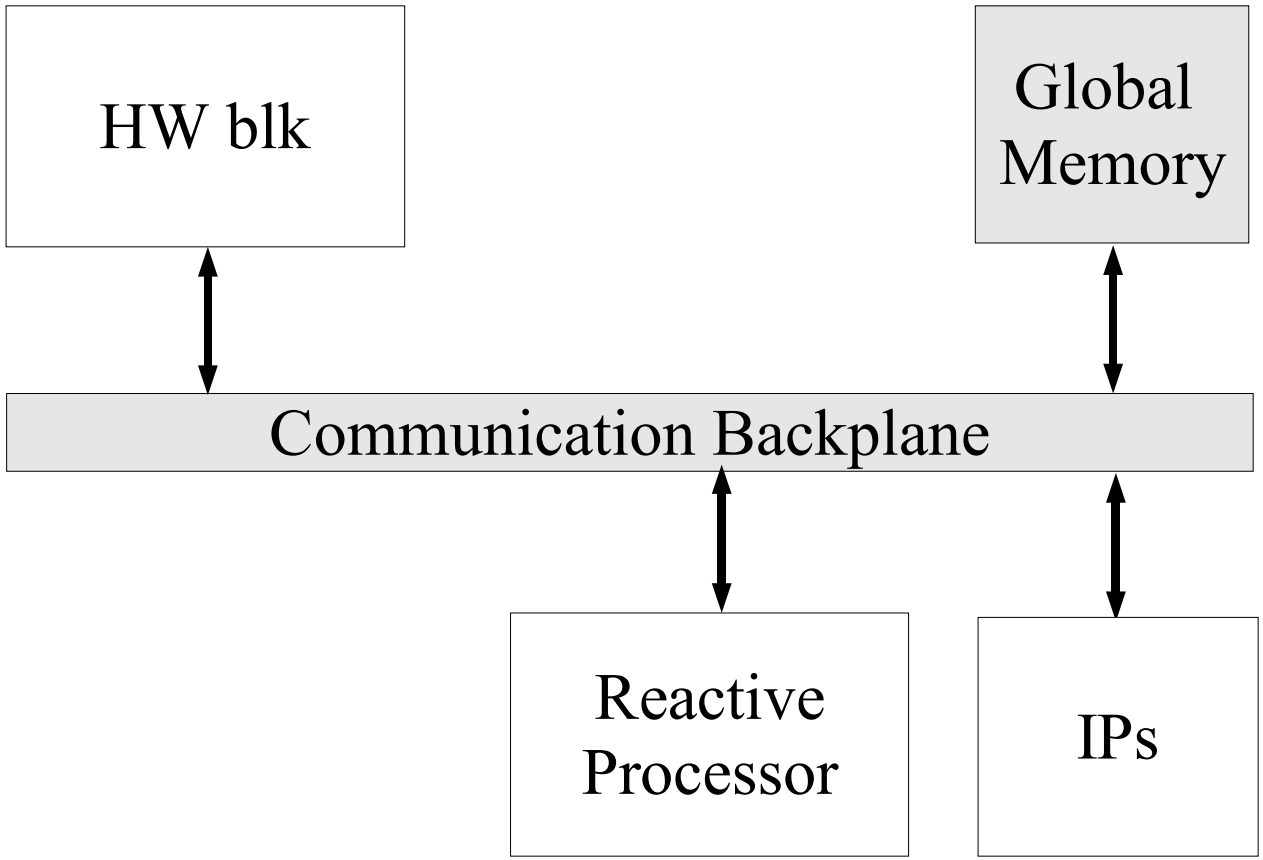
Scenario I: DSP + Reactive Processor



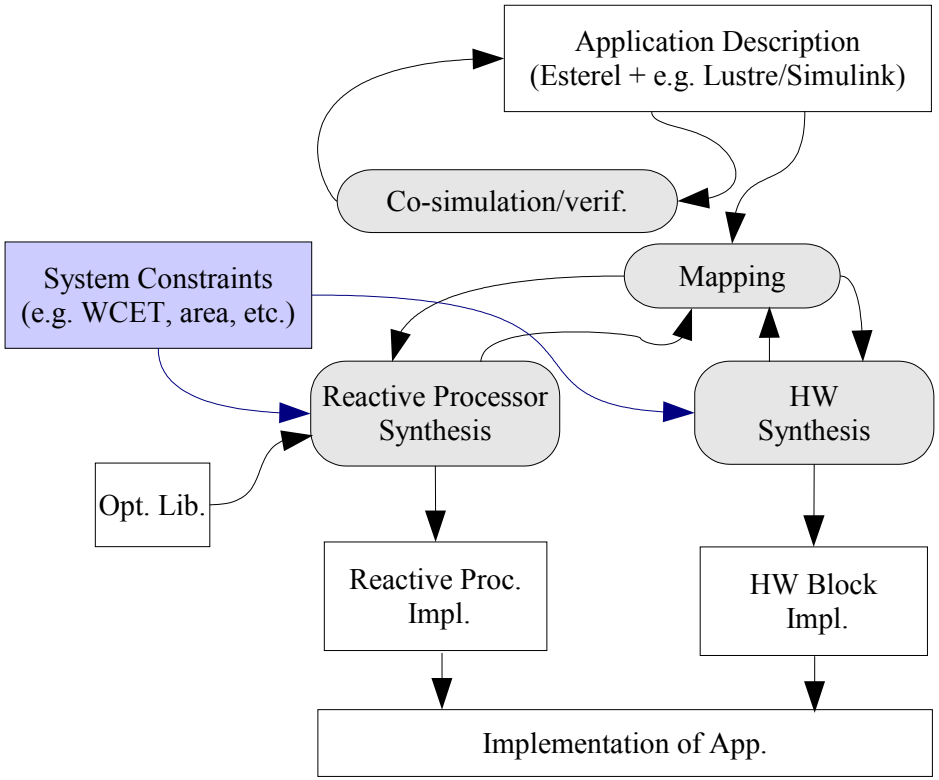
Scenario II: DSP + HW Block + Reactive Processor



Scenario III: HW Block + Reactive Processor



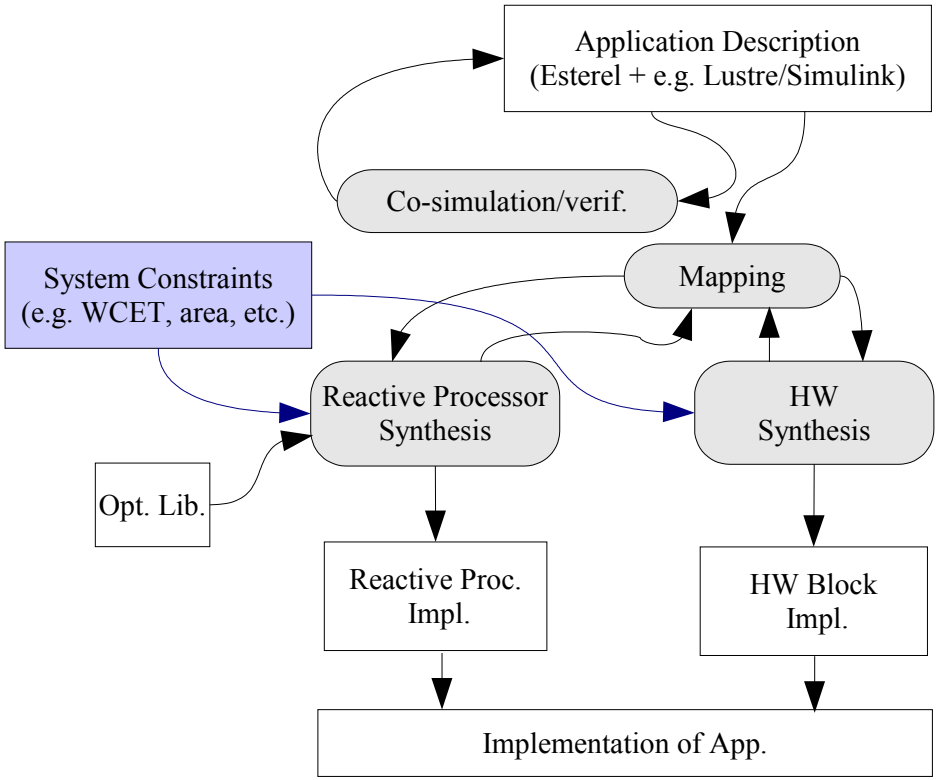
Possible Co-Design Development Flow



Reactive processing ...

- permits a simple mapping strategy
- allows optimizations on high-level
- can meet stricter constraints than classical architectures
- permits a better tradeoff between all cost factors

Possible Co-Design Development Flow



Reactive processing ...

- permits a simple mapping strategy
- allows optimizations on high-level
- can meet stricter constraints than classical architectures
- permits a better tradeoff between all cost factors

Thanks/Comments?