Sheep in wolf's clothing: Implementation models for dataflow multi-threaded software

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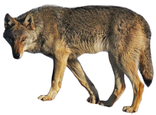
Critical systems context

Threaded implementation

Posix threads	
Non-determinism	–
Data races possible	–
Deadlocks possible	–
Asynchronous small-step semantics	–
Portability Flexibility General-purpose	+++



Critical systems context

Threaded implementation and dataflow synchronous specification

Posix threads			Dataflow synchronous formalisms
Non-determinism	−	+	Determinism
Data races possible	−	+	No data races
Deadlocks possible	−	+	No deadlocks
Asynchronous small-step semantics	−	+	Big-step semantics
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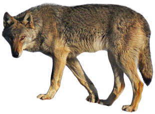

Critical systems context

Threaded implementation and dataflow synchronous specification

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Portability Flexibility General-purpose	+++		


Our thesis : in practice, threaded implementations of dataflow specification preserve a fundamentally dataflow structure

Application

Dataflow synchronous specification in Lustre

```
fun f:()->(float)
fun g:(int)->(int)
fun h:(float,int)->(int)
var
  x : float; y : int; z : int; d : int;
let
  x = f();
  y = g(d);
  z = h(x,y);
  d = 0 fby z;
tel
```

Application

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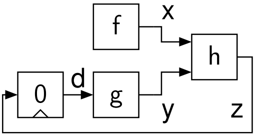

Application

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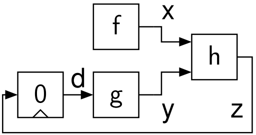


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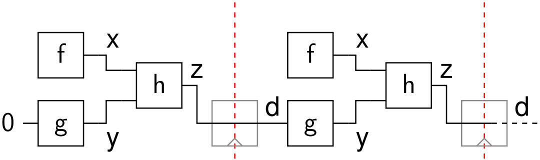
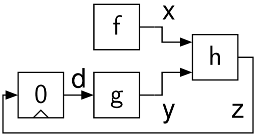


Application

Two cores implementation (static allocation and scheduling)

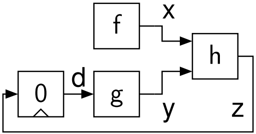



```
void thread_cpu0(){
  for(;;){
    f(&x);
    dcache_flush();



    mutex_lock(&m0);
    dcache_inval();
    h(x,y,&z);
    dcache_flush();
    mutex_unlock(&m1);
}}
```

```
void thread_cpu1(){
  for(;;){
    mutex_lock(&m1);
    dcache_inval();
    g(z,&y);
    dcache_flush();
    mutex_unlock(&m0);






}}
```

Application

Two cores implementation (static allocation and scheduling)

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void init(){
  z = 0;
  mutex_unlock(&m1);
}
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void thread_cpu0(){
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    mutex_lock(&m0);
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void thread_cpu1(){
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    mutex_lock(&m1);
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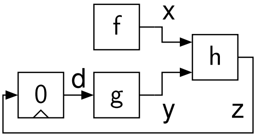
}}
```

Application

Two cores implementation (static allocation and scheduling)

```
ldscript fragment:
  x=0x22000; y=0x32000; z=0x22004; i=0x220064;
  stack0=0x30000; stack1=0x40000;
  .=0x20000; .bank2:{*(.text.cpu0);
                   .=0x100 ; *(.text.f) ;
                   .=0x500 ; *(.text.h) ;
  }
  .=0x30000; .bank3:{*(.text.cpu1);
                   .=0x200 ; *(.text.g) ;
  }
```

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    mutex_lock(&m0);
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    h(x,y,&z);
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}}
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  for(;;){
    mutex_lock(&m1);
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    g(z,&y);
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}}
```

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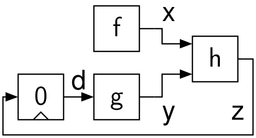


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void thread_cpu0(){
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void thread_cpu1(){
  for(;;){
    mutex_lock(&m1);
    dcache_inval();
    g(z,&y);
    dcache_flush();
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                      .=0x500 ; *(.text.h) ;
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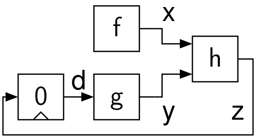



```
void init(){
  z = 0;
  mutex_unlock(&m1);
}
```

```
void thread_cpu0(){
  for(;;){
    f(&x);
    dcache_flush();

    mutex_lock(&m0);
    dcache_inval();
    h(x,y,&z);
    dcache_flush();
    mutex_unlock(&m1);
}}
```

```
void thread_cpu1(){
  for(;;){
    mutex_lock(&m1);
    dcache_inval();
    g(z,&y);
    dcache_flush();
    mutex_unlock(&m0);
}}
```

Dataflow representation of the implementation

Functional aspects

```
void init(){
  z = 0;                                   d = z fby 0
  mutex_unlock(&m1);
}
```

```
void thread_cpu0(){
  for(;;){
    f(&x);                         x  = f()
    dcache_flush();

    mutex_lock(&m0);
    dcache_inval();
    h(x,y,&z);                     z  = h(x ,y )
    dcache_flush();
    mutex_unlock(&m1);
}}
```

```
void thread_cpu1(){
  for(;;){
    mutex_lock(&m1);
    dcache_inval();
    g(z,&y);                       y  = g(d )
    dcache_flush();
    mutex_unlock(&m0);
}}
```

- Specification dataflow

Application

Two cores implementation (static allocation and scheduling)

```
void init(){
  z = 0;                                   d = z fby 0
  mutex_unlock(&m1);
}
```

```
void thread_cpu0(){
  for(;;){
    f(&x);                        x0 = f()
    dcache_flush();                x = x0

    mutex_lock(&m0);
    dcache_inval();               y0 = y
    h(x,y,&z);                    z0 = h(x0,y0)
    dcache_flush();                z = z0
    mutex_unlock(&m1);
}}
```

```
void thread_cpu1(){
  for(;;){
    mutex_lock(&m1);
    dcache_inval();                          d1 = d
    g(z,&y);                                 y1 = g(d1)
    dcache_flush();                           y = y1
    mutex_unlock(&m0);
}}
```

- Memory hierarchy representation (variable duplications)

Application

Two cores implementation (static allocation and scheduling)

```
void init(){
  z = 0;                                  d = z fby 0
  mutex_unlock(&m1);                     u1 = top fby u
}
```

```
void thread_cpu0(){
  for(;;){
    f(&x);                               x0 = f()
    dcache_flush();                       x = x0

    mutex_lock(&m0);                      _ = v
    dcache_inval();                      y0 = y
    h(x,y,&z);                           z0 = h(x0,y0)
    dcache_flush();                       z = z0
    mutex_unlock(&m1);                    u = top
}}
```

```
void thread_cpu1(){
  for(;;){
    mutex_lock(&m1);                      _ = u1
    dcache_inval();                      d1 = d
    g(z,&y);                             y1 = g(d1)
    dcache_flush();                       y = y1
    mutex_unlock(&m0);                    v = top
}}
```

- Mutex operations

Dataflow representation of the implementation

Dataflow synchronous implementation model

```
fun f:()->(float)
fun g:(int)->(int)
fun h:(float,int)->(int)
var
  x:int y:float z:int d:int
  x0:int y0:float y1:float
  z0:int d1:int
  u:event u1:event v:event
let
  d = 0 fby z
  u1 = top fby u

  x0 = f()
   x = x0

   _ = u1
  d1 = d
  y1 = g(d1)
   y = y1
   v = top

   _ = v
  y0 = y
  z0 = h(x0,y0)
   z = z0
   u = top
tel
```

- Statements all interpreted, but no structure nor sequencing

Dataflow representation of the implementation

Extended dataflow synchronous implementation model

```
fun f:()->(float)
fun g:(int)->(int)
fun h:(float,int)->(int)
var
  x:int y:float z:int d:int
  x0:int y0:float y1:float
  z0:int d1:int
  u:event u1:event v:event s0,s1,s2,s3,s4,s5,s6,s7,t0,t1,t2,t3:event
let
  d = 0 fby z
  u1 = top fby u
  s7 = top fby s6
```

```
    wait(s7) done(s0)                    x0 = f()
    wait(s0) done(s1)                     x = x0
```

```
    done(t0)                              _ = u1
    wait(t0) done(t1)                    d1 = d
    wait(t1) done(t2)                    y1 = g(d1)
    wait(t2) done(t3)                     y = y1
    wait(t3)                              v = top
```

```
    wait(s1) done(s2)                     _ = v
    wait(s2) done(s3)                    y0 = y
    wait(s3) done(s4)                    z0 = h(x0,y0)
    wait(s4) done(s5)                     z = z0
    wait(s5) done(s6)                     u = top
tel
```

- Explicit sequencing
- Functionally complete : same traces as C code under async. semantics

Dataflow representation of the implementation

Non-functional annotations

```
fun f:()->(float)
fun g:(int)->(int)
fun h:(float,int)->(int)
var
  x:int y:float z:int d:int
  x0:int y0:float y1:float
  z0:int d1:int
  u:event u1:event v:event s0,s1,s2,s3,s4,s5,s6,s7,t0,t1,t2,t3:event
let
  d = 0 fby z
  u1 = top fby u
  s7 = top fby s6
thread
    wait(s7) done(s0)          x0 = f()
    wait(s0) done(s1)           x = x0

    wait(s1) done(s2)           _ = v
    wait(s2) done(s3)          y0 = y
    wait(s3) done(s4)          z0 = h(x0,y0)
    wait(s4) done(s5)           z = z0
    wait(s5) done(s6)           u = top
tel
```

```
thread
    done(t0)                    _ = u1
    wait(t0) done(t1)          d1 = d
    wait(t1) done(t2)          y1 = g(d1)
    wait(t2) done(t3)           y = y1
    wait(t3)                    v = top
```

- Thread structure

Dataflow representation of the implementation

Non-functional annotations

```
fun f:()->(float) at 0x20100
fun g:(int)->(int) at 0x30300
fun h:(float,int)->(int) at 0x20500
var
  x:int at 0x22000 y:float at 0x32000 z:int at 0x22004 d:int at z
  x0:int at x on cpu0 y0:float at y on cpu0 y1:float at y on cpu1
  z0:int at z on cpu0 d1:int at z on cpu1
  u:event at m1 u1:event at m1 v:event at m0 s0,s1,s2,s3,s4,s5,s6,s7,t0,t1,t2,t3:event
let
  d = 0 fby z
  u1 = top fby u
  s7 = top fby s6
thread on cpu0 at 0x20000 stack 0x30000
    wait(s7) done(s0)          x0 = f()
    wait(s0) done(s1)           x = x0

    wait(s1) done(s2)           _ = v
    wait(s2) done(s3)          y0 = y
    wait(s3) done(s4)          z0 = h(x0,y0)
    wait(s4) done(s5)           z = z0
    wait(s5) done(s6)           u = top
thread on cpu1 at 0x30000 stack 0x40000
    done(t0)                    _ = u1
    wait(t0) done(t1)          d1 = d
    wait(t1) done(t2)          y1 = g(d1)
    wait(t2) done(t3)           y = y1
    wait(t3)                    v = top
tel
```

- Allocation

Dataflow representation of the implementation

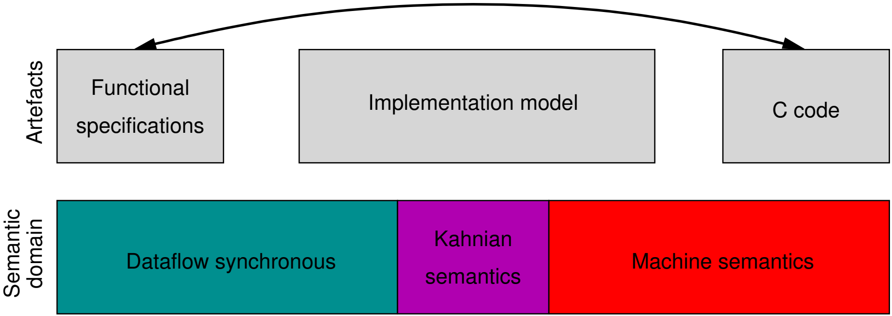
Non-functional annotations

```
fun f:()->(float) at 0x20100
fun g:(int)->(int) at 0x30300
fun h:(float,int)->(int) at 0x20500
var
  x:int at 0x22000 y:float at 0x32000 z:int at 0x22004 d:int at z
  x0:int at x on cpu0 y0:float at y on cpu0 y1:float at y on cpu1
  z0:int at z on cpu0 d1:int at z on cpu1
  u:event at m1 u1:event at m1 v:event at m0 s0,s1,s2,s3,s4,s5,s6,s7,t0,t1,t2,t3:event
let
  d = 0 fby z
  u1 = top fby u
  s7 = top fby s6
thread on cpu0 at 0x20000 stack 0x30000
    wait(s7) done(s0)                        x0 = f()
    wait(s0) done(s1) [flush:0x22000]         x = x0

    wait(s1) done(s2) [lock:m0]               _ = v
    wait(s2) done(s3) [inval:0x32000] y0 = y
    wait(s3) done(s4)                        z0 = h(x0,y0)
    wait(s4) done(s5) [flush:0x22004]         z = z0
    wait(s5) done(s6) [unlock:m1]             u = top
thread on cpu1 at 0x30000 stack 0x40000
    done(t0)                   [lock:m1]             _ = u1
    wait(t0) done(t1) [inval:0x22004] d1 = d
    wait(t1) done(t2)                        y1 = g(d1)
    wait(t2) done(t3) [flush:0x32000]     y = y1
    wait(t3)                   [unlock:m0]          v = top
tel
```

- Machine semantics of memory coherency and synchronization operations

Proving the correctness of an implementation



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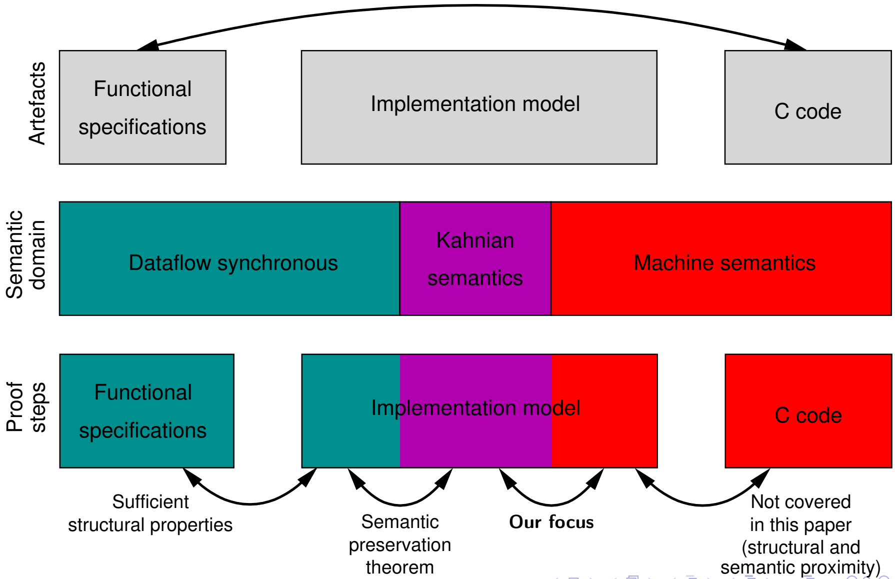

Correction formalization

From asynchronous to machine semantics

The proof is not complete, we merely provide a paper formalization of the proof objectives.

- **Implementability of the Kahnian interpretation**
  - Boundedness: Every FIFO of the Kahn network must be statically bounded for implementation in memory
  - Explicit synchronizations: Synchronization no longer on the data but exclusively on pure synchronization `event` variables
- **Mapping correctness**
  - Execution without errors: Execution under machine semantics do not lead to error state (static check of synchronization behavior)
  - Semantic preservation: Same sequence of inputs of function in Kahnian and machine semantics

Conclusion

Main claim : in practice, threaded implementations of dataflow specification preserve a fundamentally dataflow structure

- True for implementations we synthesize
- Future work : determine if it is true for other implementation methods

Impact on implementation correctness proof ?

- Proposal for new proof structuring (on paper)
- It is still difficult (future work)

No real-time yet

- Future work