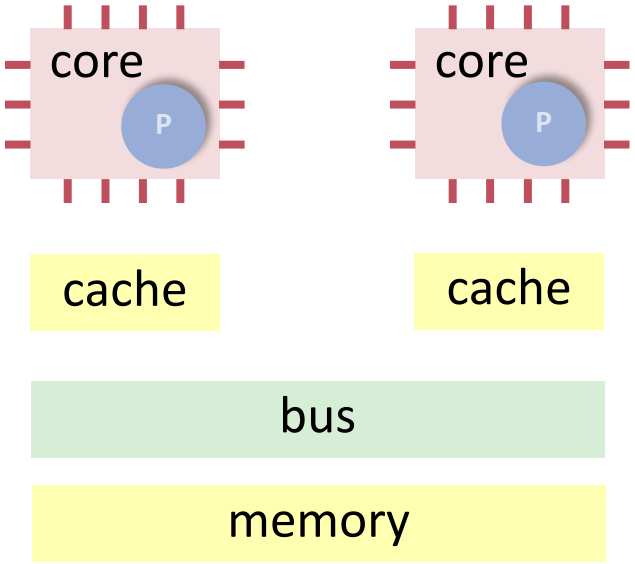
Active Cells:

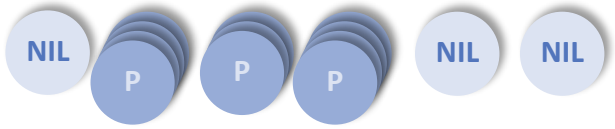
A Programming Model for Configurable Multicore Systems

CASE STUDY 4: CUSTOM DESIGNED MULTI-PROCESSOR SYSTEM

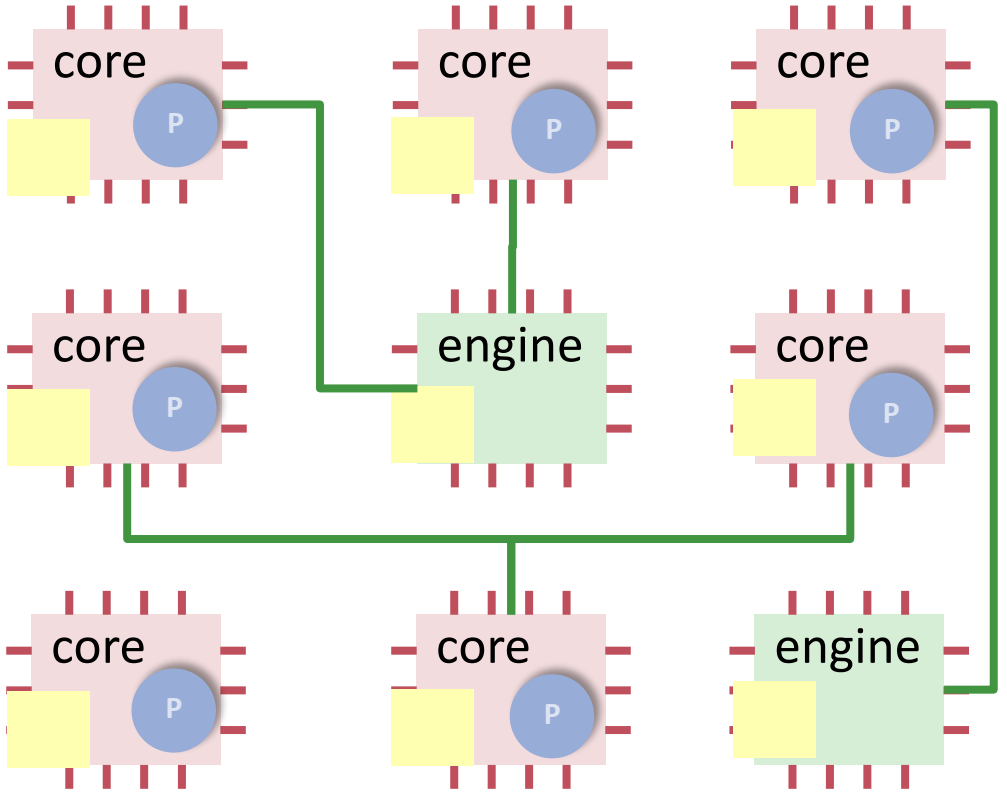
Vision

General Purpose Shared Memory Computer





Application Specific Multicore Network On Chip



Motivation: Multicore Systems Challenges

- Cache Coherence
- Shared Memory Communication Bottleneck
- Thread Synchronization Overhead

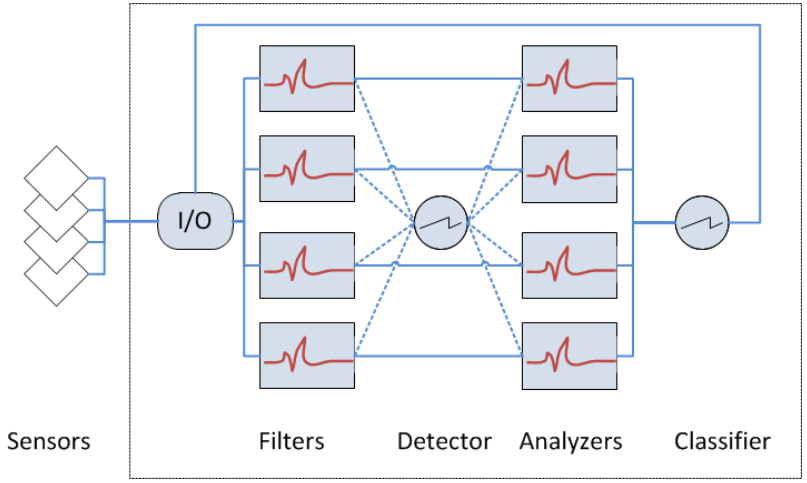
⇨ Hard to predict performance of a program

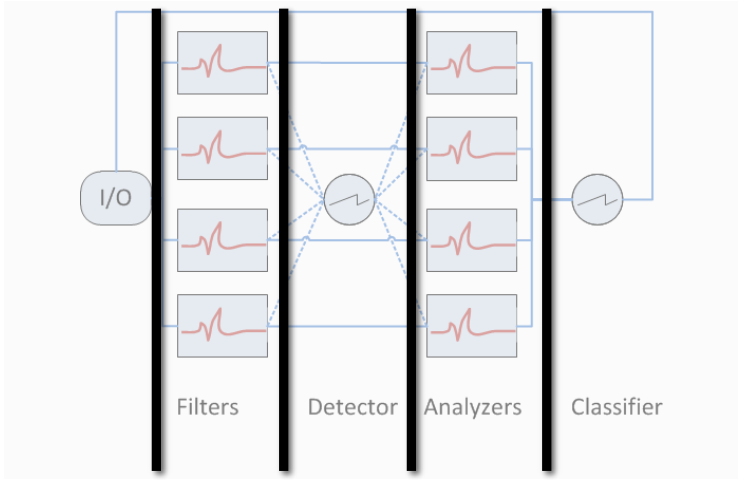
⇨ Difficult to scale the design to massive multi-core architecture

Operating System Challenges

- Processor Time Sharing
  - Interrupts
  - Context Switches
  - Thread Synchronisation
- Memory Sharing
  - Inter-process: Paging
  - Intra-process, Inter-Thread: Monitors

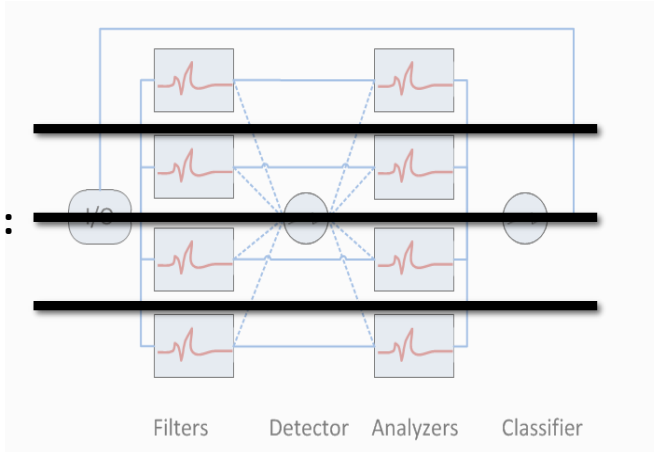
Focus: Streaming Applications

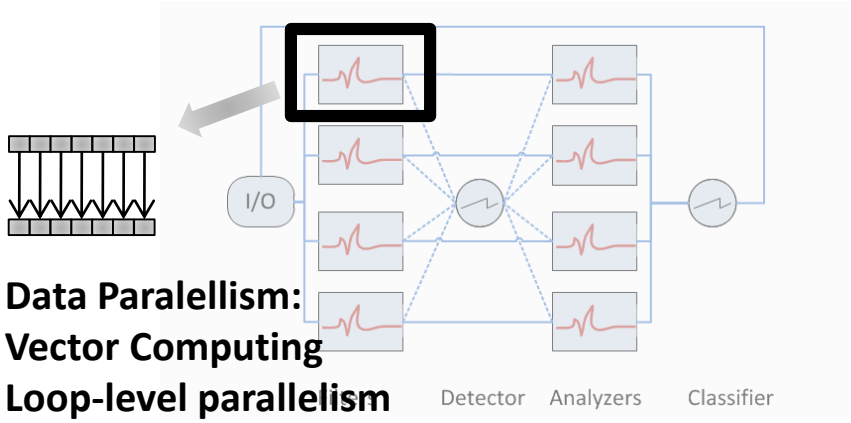




Stream-Parallelism: Pipelining

Task Parallelism: Parallel Execution





Data Paralellism: Vector Computing Loop-level parallelism

4.1. HARDWARE BUILDING BLOCKS TRM AND INTERCONNECTS

TRM: Tiny **R**egister **M**achine*

- Extremely simple processor on FPGA with Harvard architecture.
- Two-stage pipelined
- Each TRM contains
  - Arithmetic-logic unit (ALU) and a shifter.
  - 32-bit operands and results stored in a bank of 2*8 registers.
  - local data memory: d*512 words of 32 bits.
  - local program memory: i*1024 instructions with 18 bits.
  - 7 general purpose registers
  - Register H for storing the high 32 bits of a product, and 4 conditional registers C, N, V, Z.
- No caches

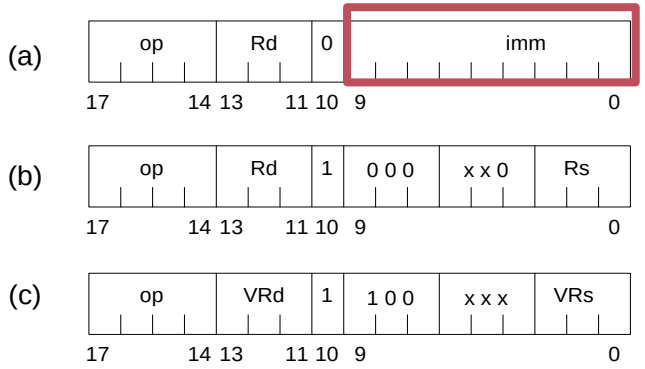
* Invented and implemented by Dr. Ling Liu and Prof. Niklaus Wirth

TRM Machine Language

- Machine language: binary representation of instructions
- 18-bit instructions
- Three instruction types:
  - Type a: arithmetical and logical operations
  - Type b: load and store instructions
  - Type c: branch instructions (for jumping)

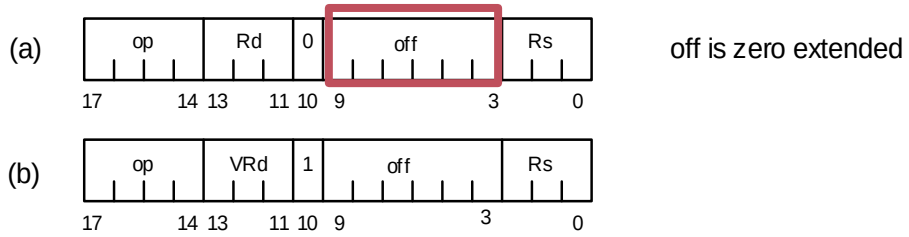
Encoding Overview

- Register Operations



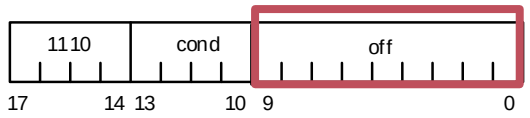
imm is zero extended to 32 bits

- Load and Store



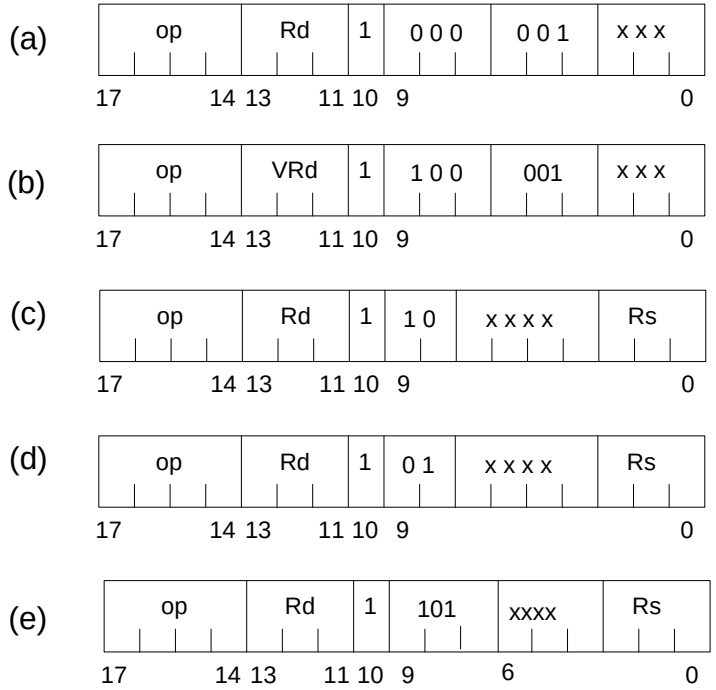
off is zero extended

- Conditional Branches

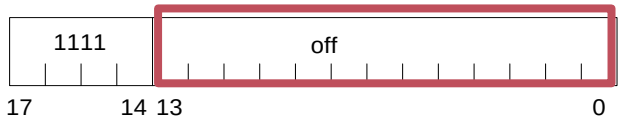


off is sign extended

- Special Instructions



- Branch and Link



off is 14-bit offset

TRM architecture

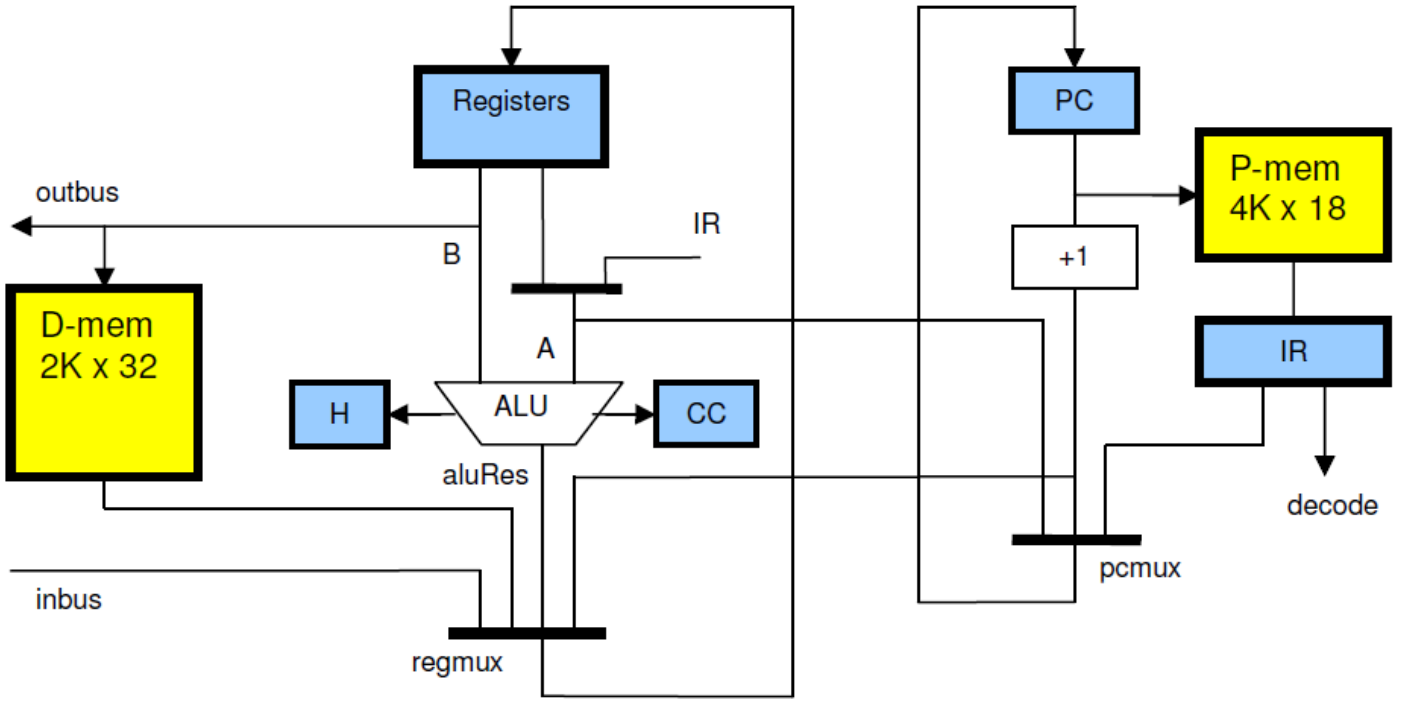


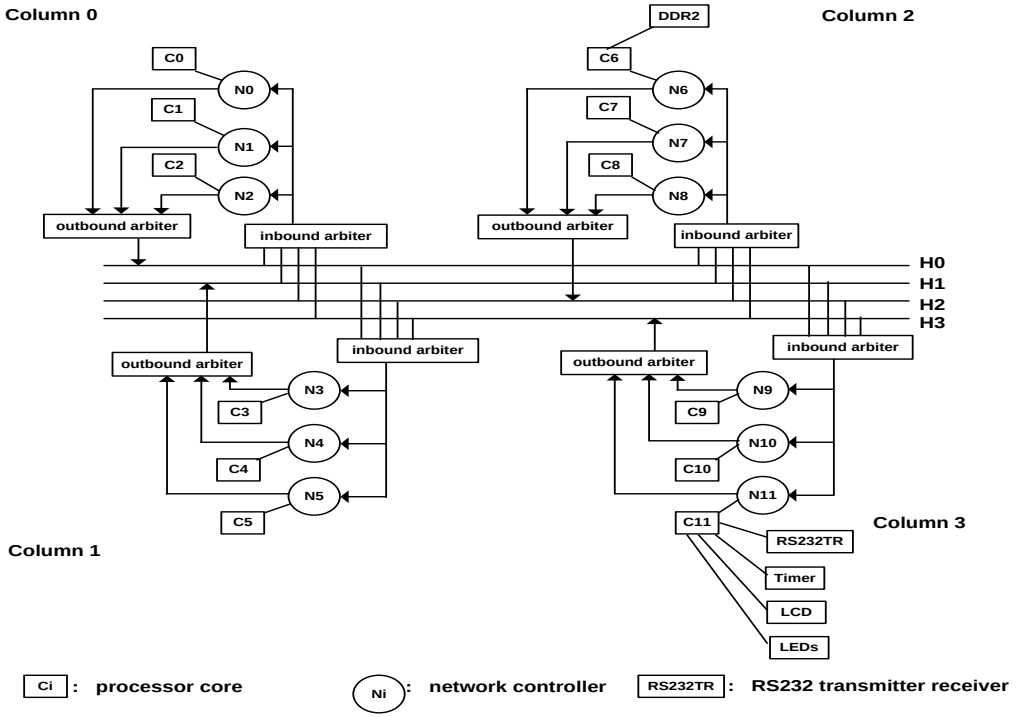
Figure from: Niklaus Wirth, *Experiments in Computer System Design*, Technical Report, August 2010
http://www.inf.ethz.ch/personal/wirth/Articles/FPGA-relatedWork/ComputerSystemDesign.pdf

Variants of TRM

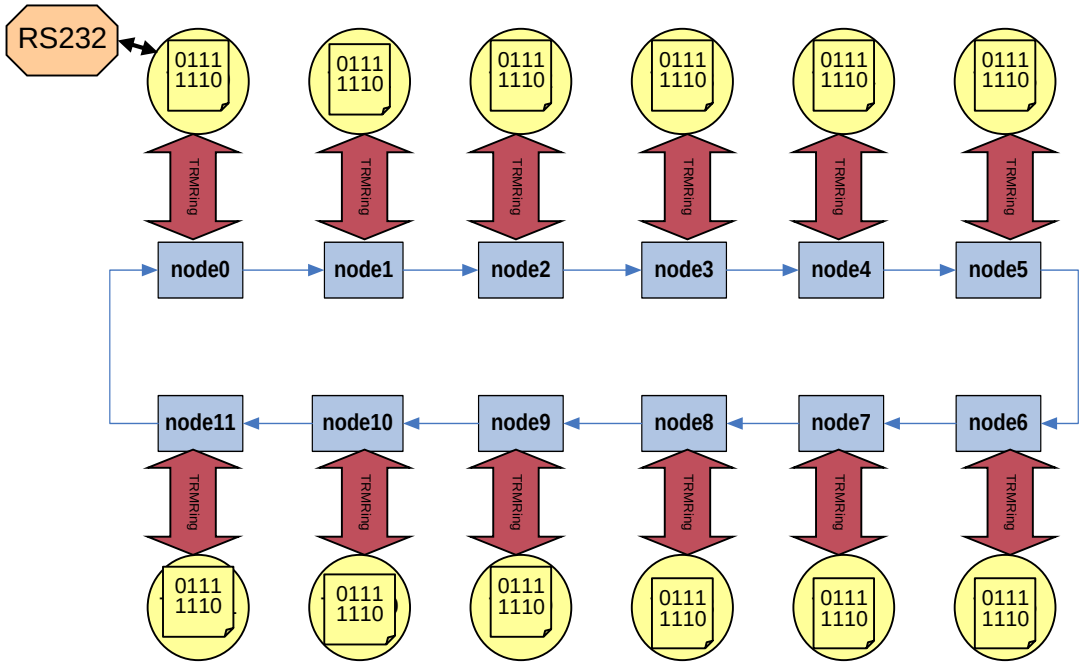
- FTRM
  - includes floating point unit
- VTRM (Master Thesis Dan Tecu)
  - includes a vector processing unit
  - supports 8 x 8-word registers
  - available with / without FP unit
- TRM with software-configurable instruction width
  (Master Thesis Stefan Koster, 2015)

Initial Experiments

TRM12 Bus



TRM12 Ring

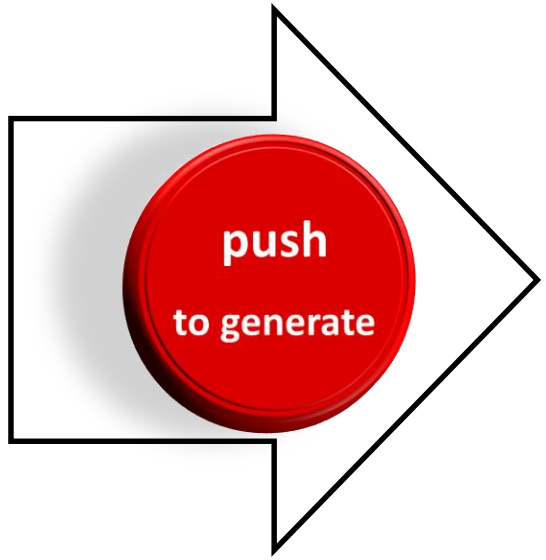


4.2. HARDWARE SOFTWARE CODESIGN

Software / Hardware Co-design

Vision: Custom System on Button Push

System design as high-level program code



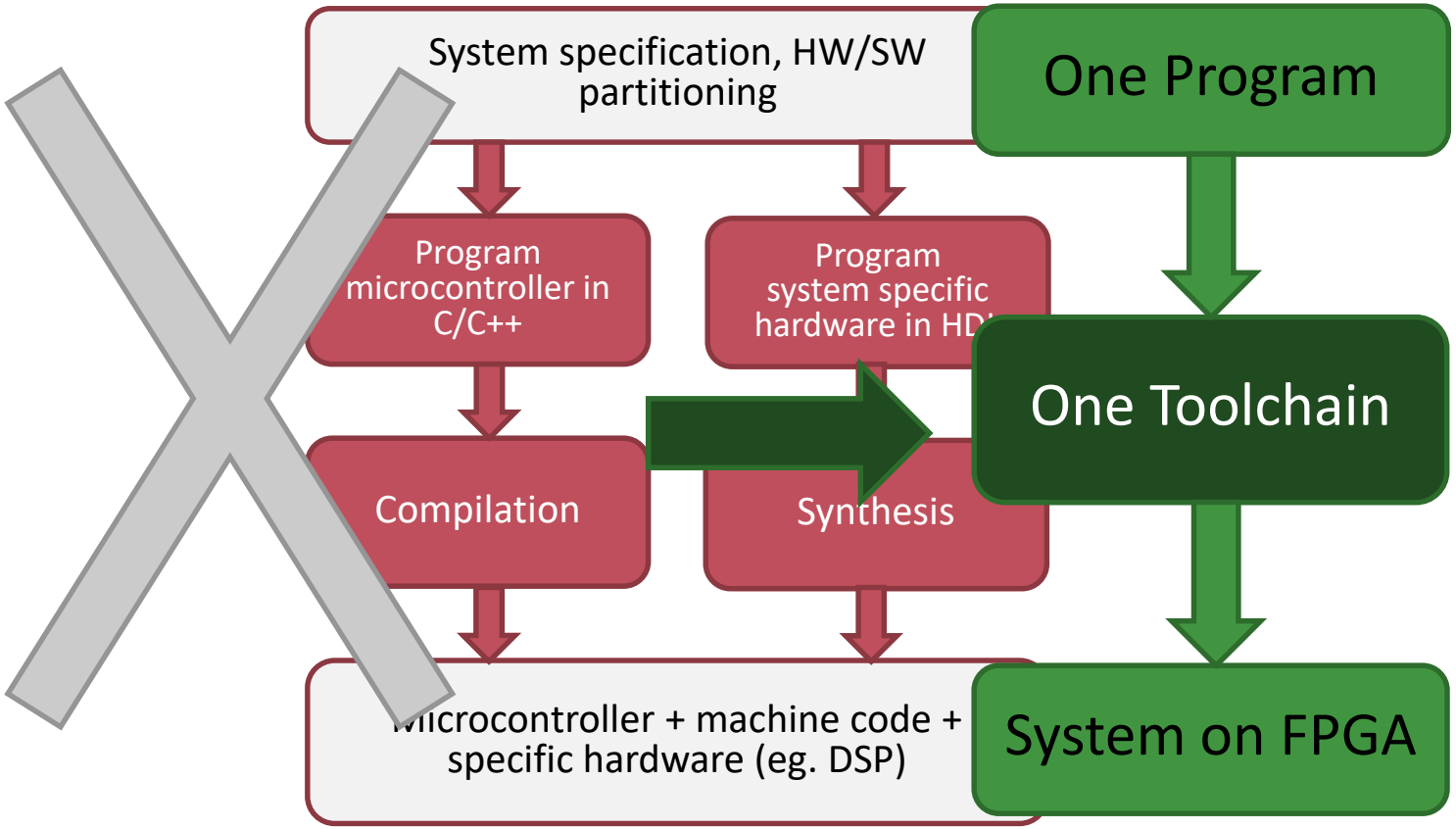
Electronic circuits

Computing model
Programming Language

Compiler, Synthesizer, Hardware Library, Simulator

Programmable Hardware (FPGA)

Traditional HW/SW co-design



Traditional HW/SW co-design for embedded systems

Active Cells approach for embedded systems development

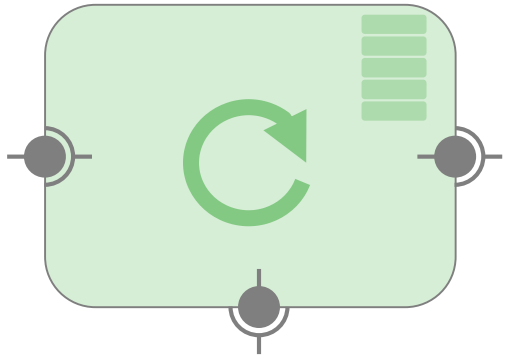
Active Cells Computing Model

Inspired by
- Kahn Process Networks
- Dataflow Programming
- CSP (e.g. Google's Go)
- Actor Model (e.g. Erlang)

On-chip distributed system

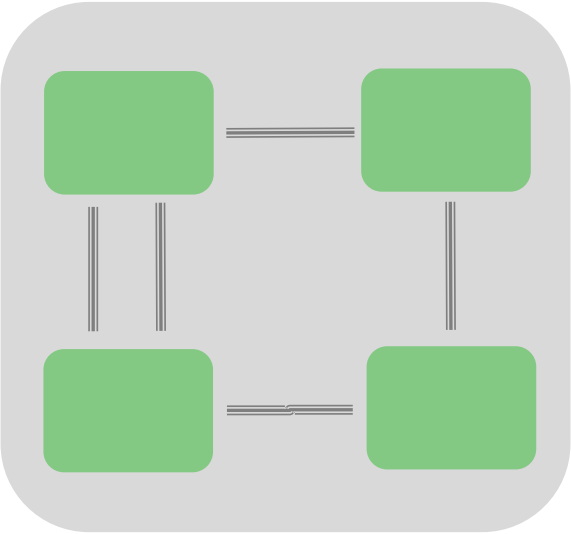
Cell

- Scope and environment for a running **isolated process**.
- Integrated **control thread**(s)
- Provides **communication ports**

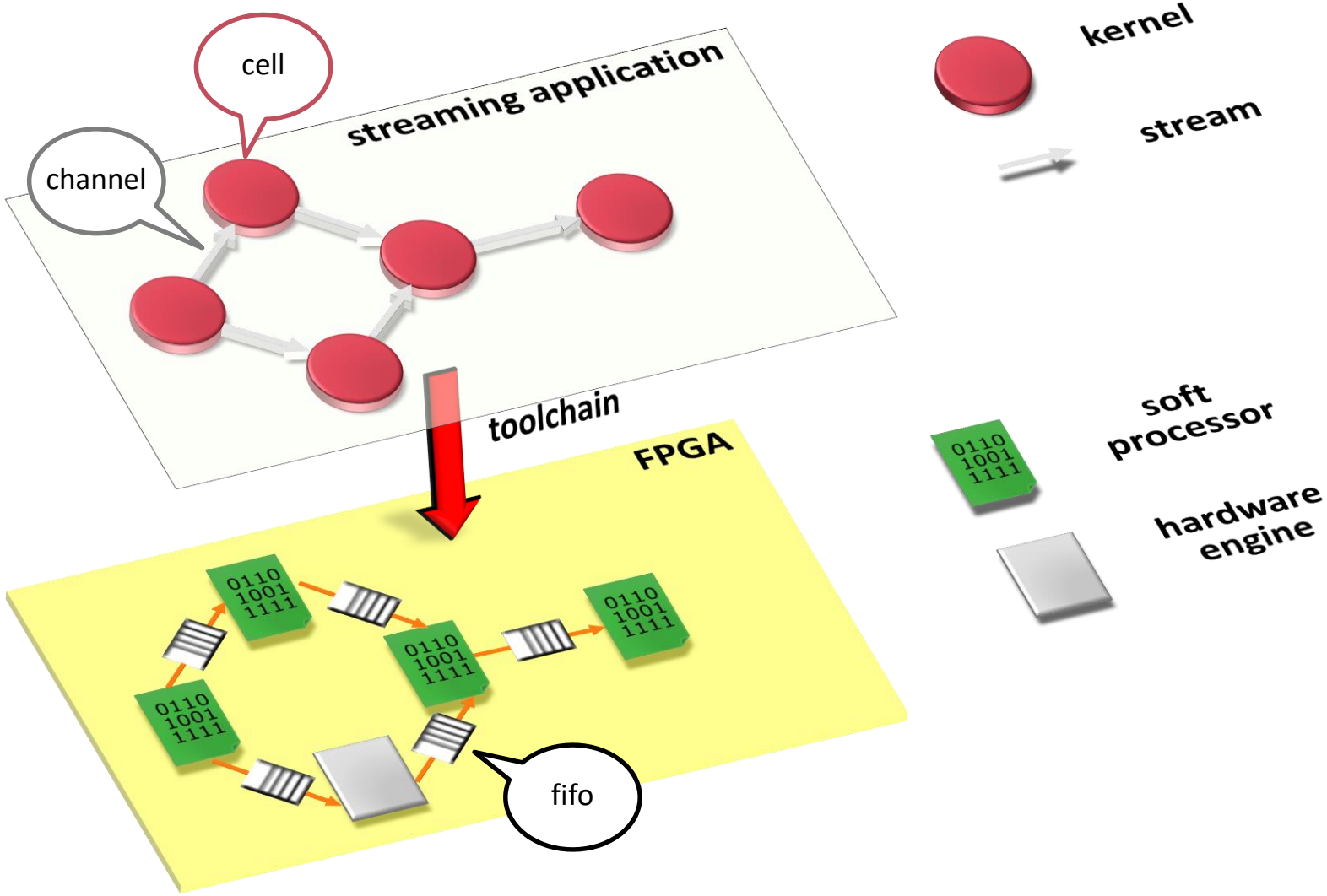


Net

- **Network** of communication cells
- Cells connected via **channels** (FIFOs)



Software → Hardware Map



Consequences of the approach

- No global memory
- No processor sharing
- No pecularities of specific processor
- No predefined topology (NoC)
- No interrupts

➔ **No operating system**

Cell

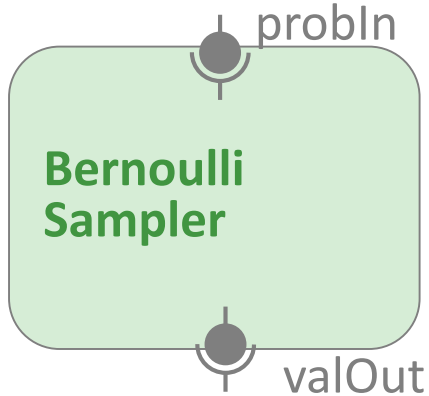
non-typed communication ports

```
type
BernoulliSampler* = cell (probIn: port in; valOut: port out);
var
   r: Random.Generator;
   p: real;
begin
   new(r);
   loop
      p << probIn;
      valOut << r.Bernoulli(p);
   end
end BernoulliSampler;
```

blocking receive

asynchronous send

Cell Activity

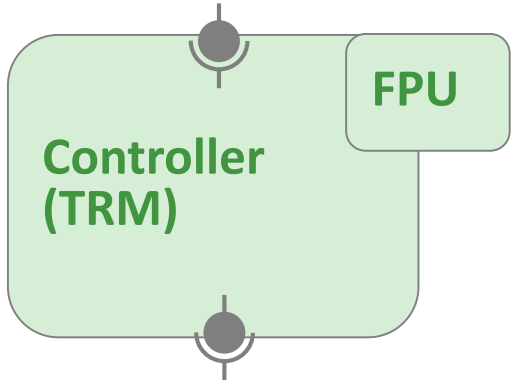


Properties

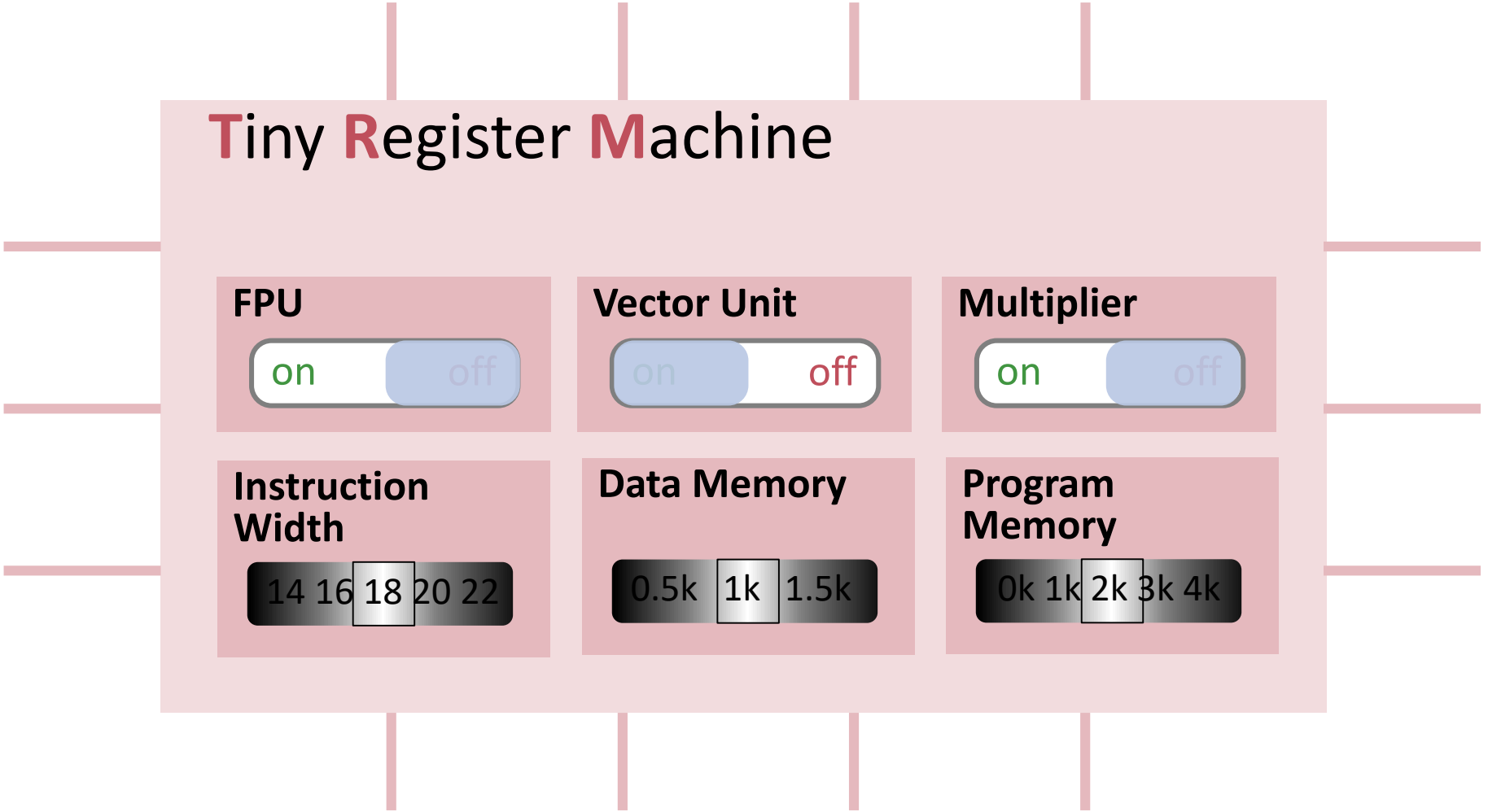
Properties can influence both, generation of hardware and the generation of software code.

```
type
   Controller = cell {Processor=TRM, FPU, DataMemory=2048, BitWidth=18}
                (in: port in (64); result: port out);
   ...

   begin
      (* ... controller action ... *)
   end Controller;
....
```

Port Width



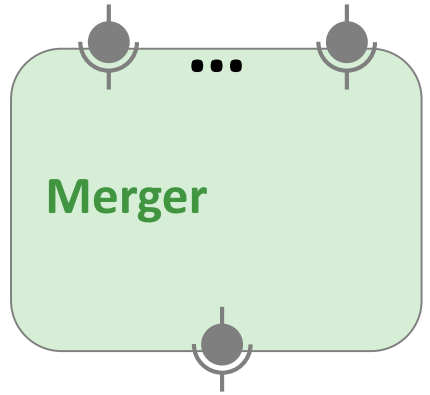
Configurable Processor on PL



Engine

```
type
Merger = cell {Engine, inputs=1}
     (ind: array inputs of port in; outd: port out);
var data: longint;
begin
     loop
        for i := 0 to len(in)-
           data << ind[i]
           outd << data;
        end
     end
  end Merger;
```

Engines are prebuilt components instantiated as electronic circuits on a target hardware

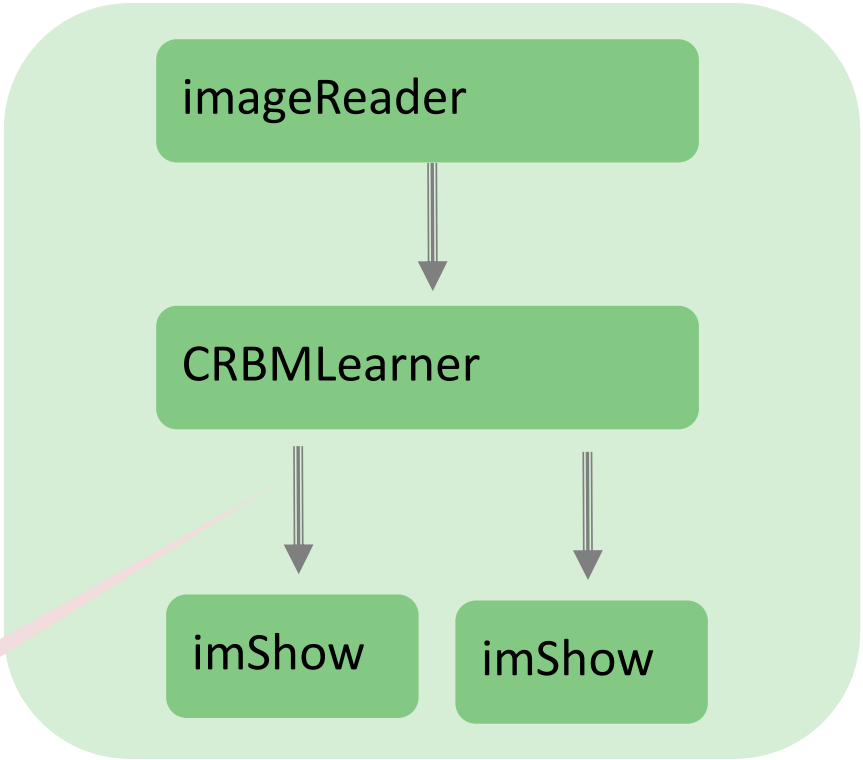


Unit of Deployment: (Terminal) Cellnet

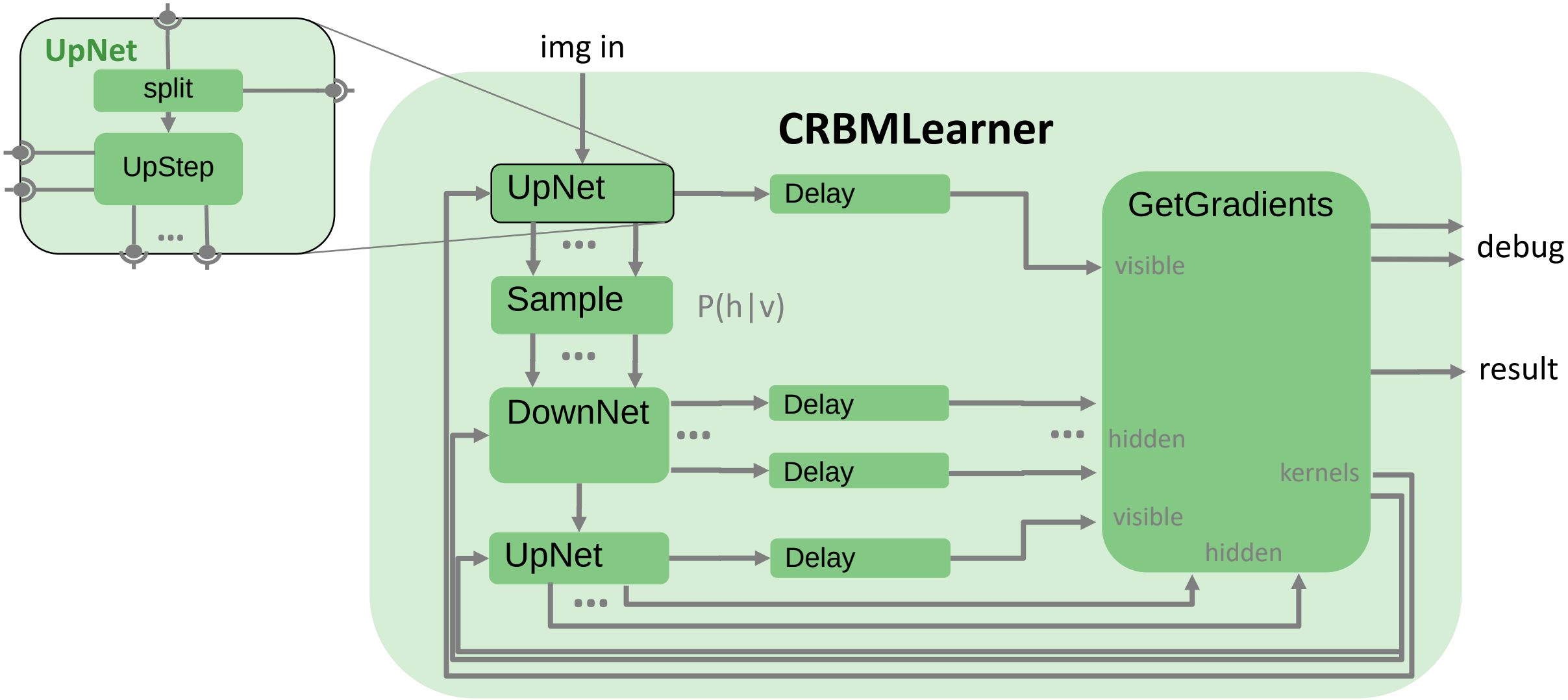
```
LearnTest = cellnet;
var
   learner: CRBMNet.CRBMLearner;
   reader: MLUtil.imageReader;
   ims0,ims1: MLUtil.imshow;
   …
begin
   new(learner)
   new(reader);
   new(ims0{name='v0debug',posx=0,posy=100});
   new(ims1{name='v1debug',posx=300,posy=100});
   …
   reader.imageOUT >> learner.imgIN;
   learner.v0DebugOUT >> ims0.imageIN;
   learner.v1DebugOUT >> ims1.imageIN;
   …
end LearnTest;
```

dynamic construction

connection



Hierarchical Composition

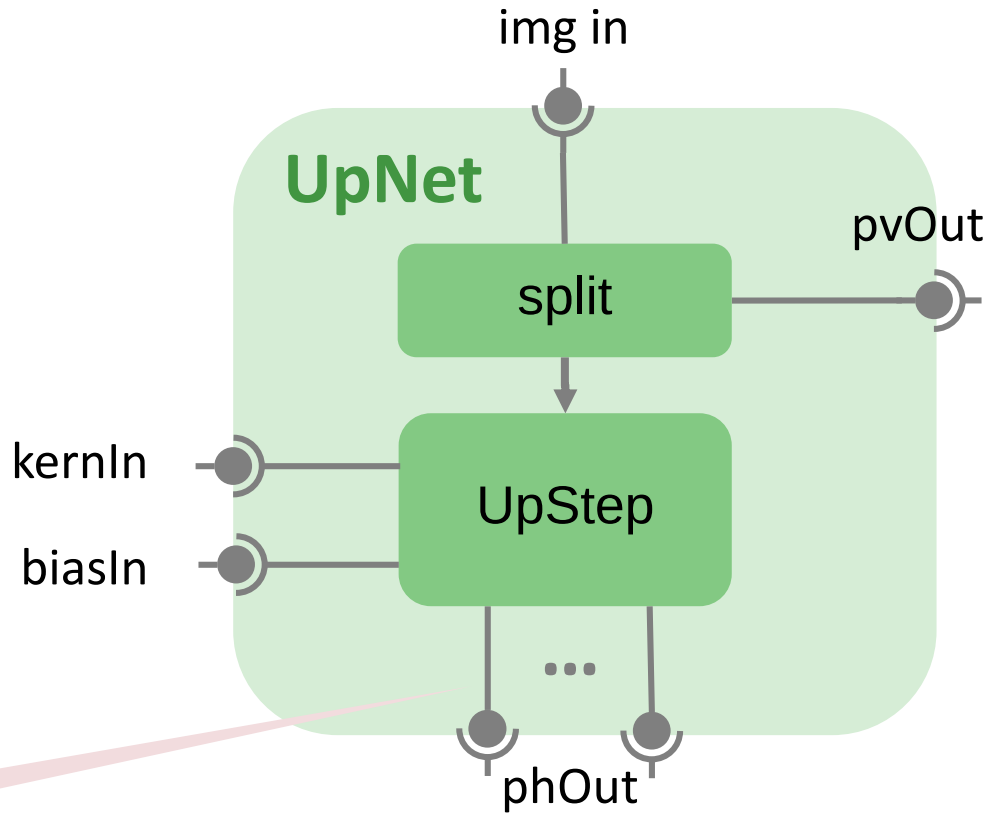


Hierarchic Composition: non-terminal Cellnet

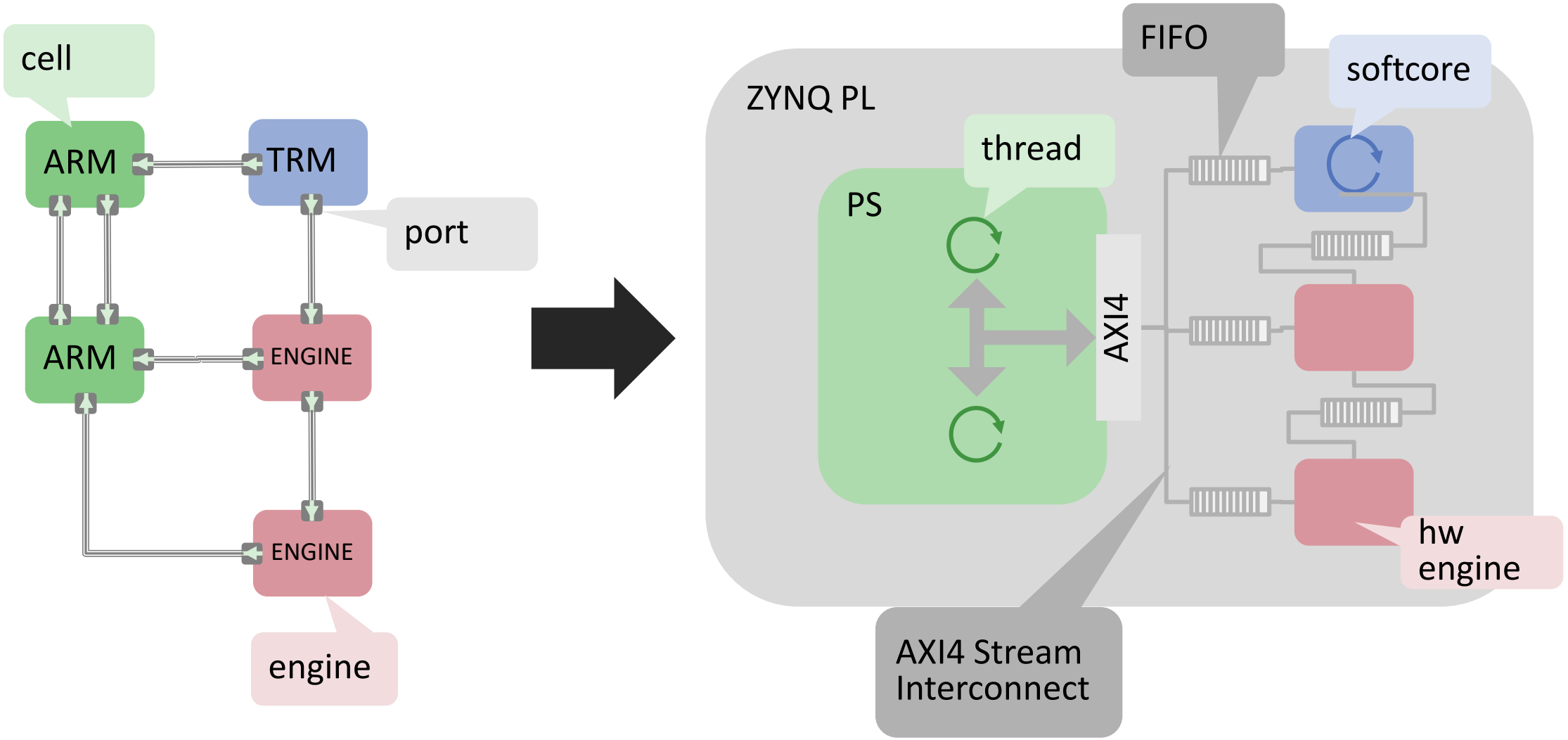
```
UpNet = cellnet
    {vr=28,vc=28,kr=5,kc=5,k=9,c=2,name='upstep'}
    (pvIN, kerIN, bIN : port in;  phOUT: array k of port out; pvSideOUT: port out );
var
    i,hr,hc: longint;
    upstep: CRBMUpstepCell;
    split: MLFunctions.SplitterCell;
begin
    hr:=vr-kr+1; hc:=vc-kc+1;
    new(vSplit {dataSize=vr*vc,numOut=2});
    new(upstep {vr=vr,vc=vc,kr=kr,kc=kc,k=k,c=c});
    pvIN >> vSplit.dataIN;
    vSplit.dataOUT[0] >> pvSideOUT;
    vSplit.dataOUT[1] >> UpstepCell.vIN;
    kerIN >> UpstepCell.kerIN;
    bIN >> UpstepCell.bIN;
    for i:=0 to k-1 do
        upstep.phOUT[i] >> phOUT[i];
    end;
end CRBMUpNet;
```

ports and properties

port delegation

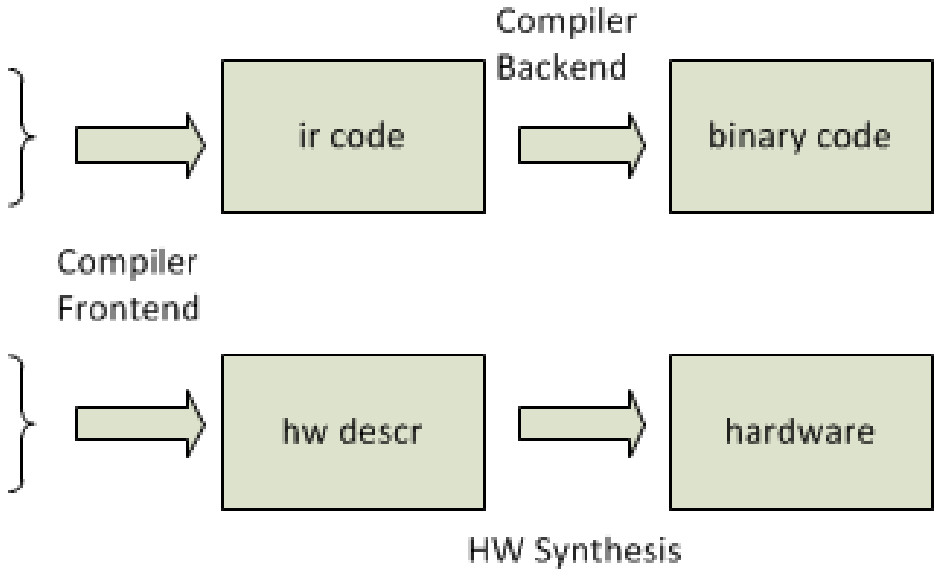


Software → Hardware Map



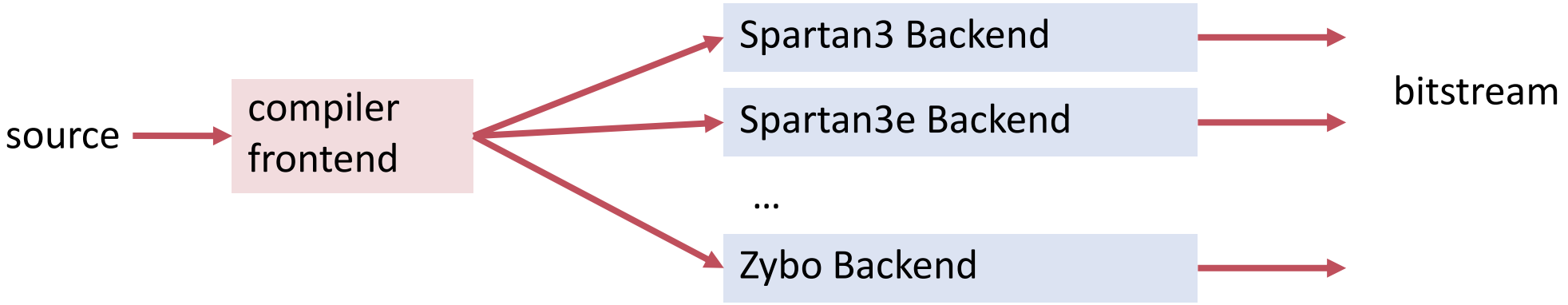
Hybrid Compilation

```
cellnet N;

type A=cell(pi: port in; po: port out);
var x: integer;
begin
… pi ? x; … po ! x; …
end A;

var a,b: A;
begin
… connect(a.po, b.pi)
end N.
```



Code body	Role	Compilation method
Cell (Softcore)	Program logic	Software Compilation
Cell (Engine)	Computation unit	Hardware Generation
Cell Net	Architecture	Hardware Compilation

Implementation Alternatives (1)



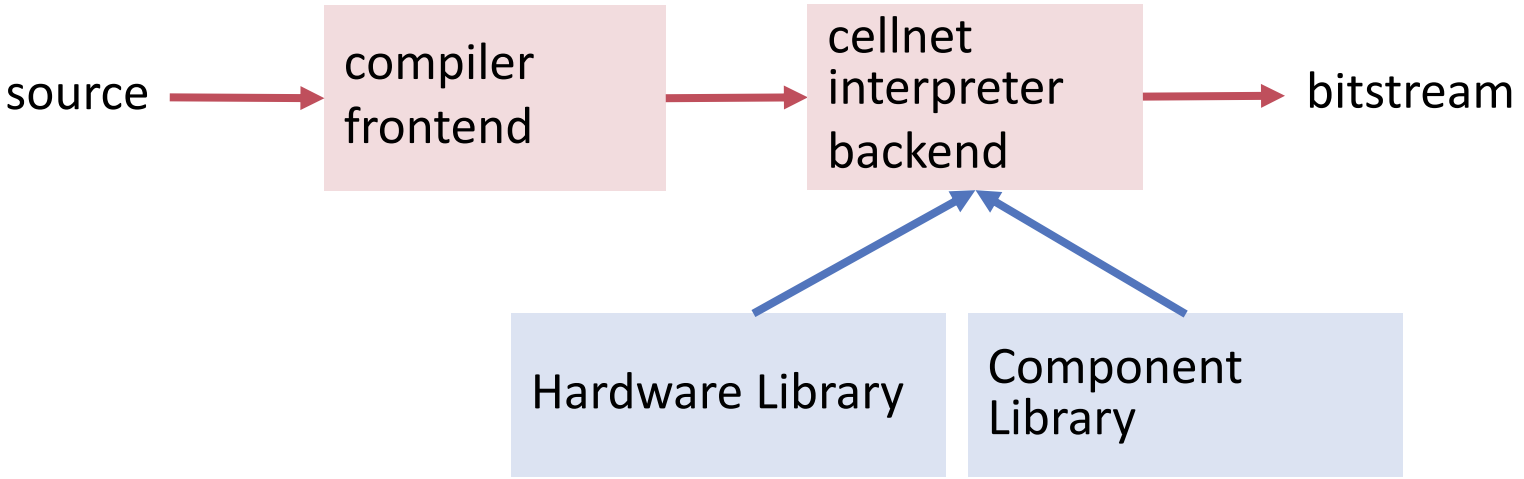
+ simple

- redundant

- not flexible

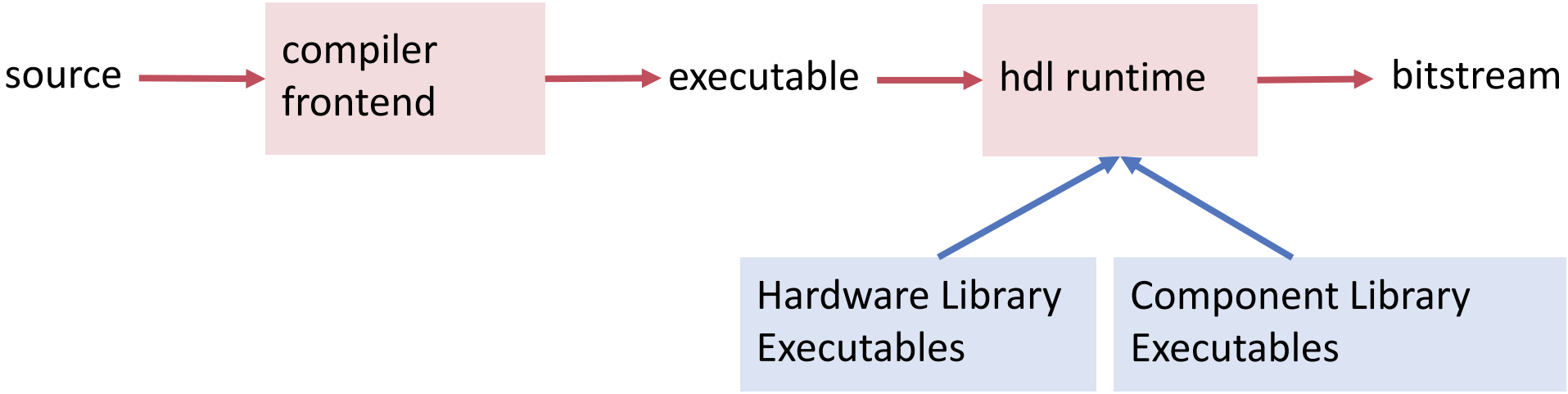
- hard to extend

Implementation Alternatives (2)



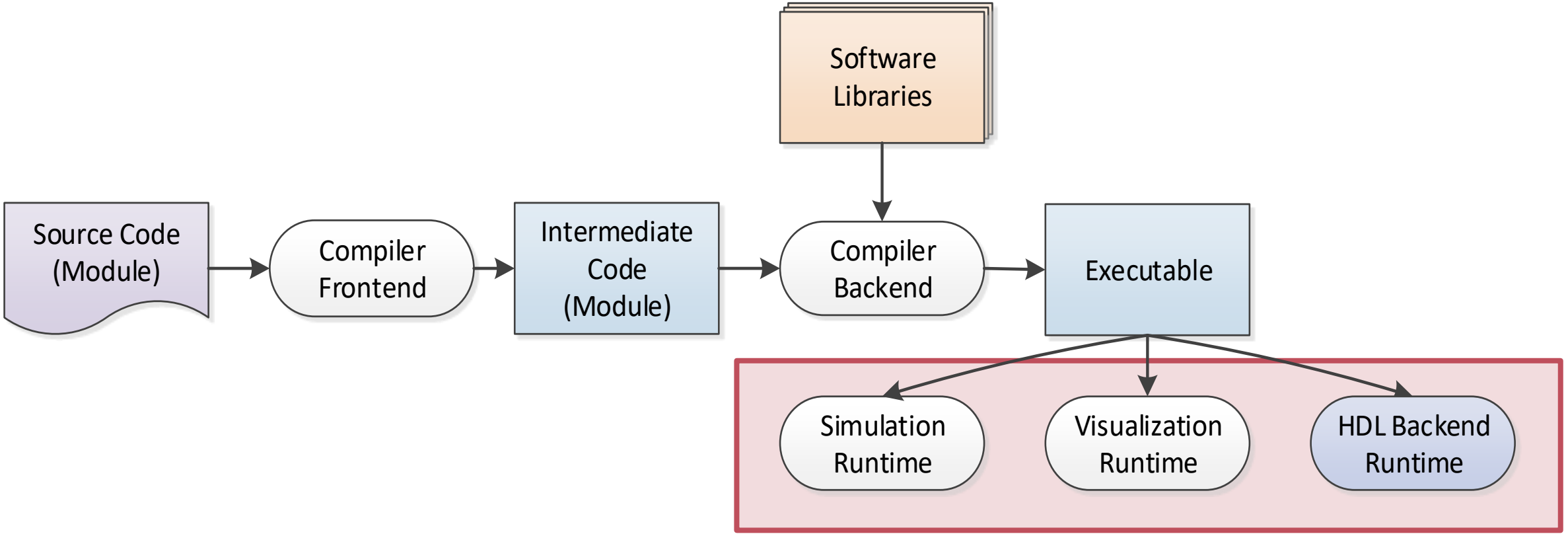
+ extensible
+ not redundant
- not simple
- static configuration limits flexibility

Implementation Alternatives (3)

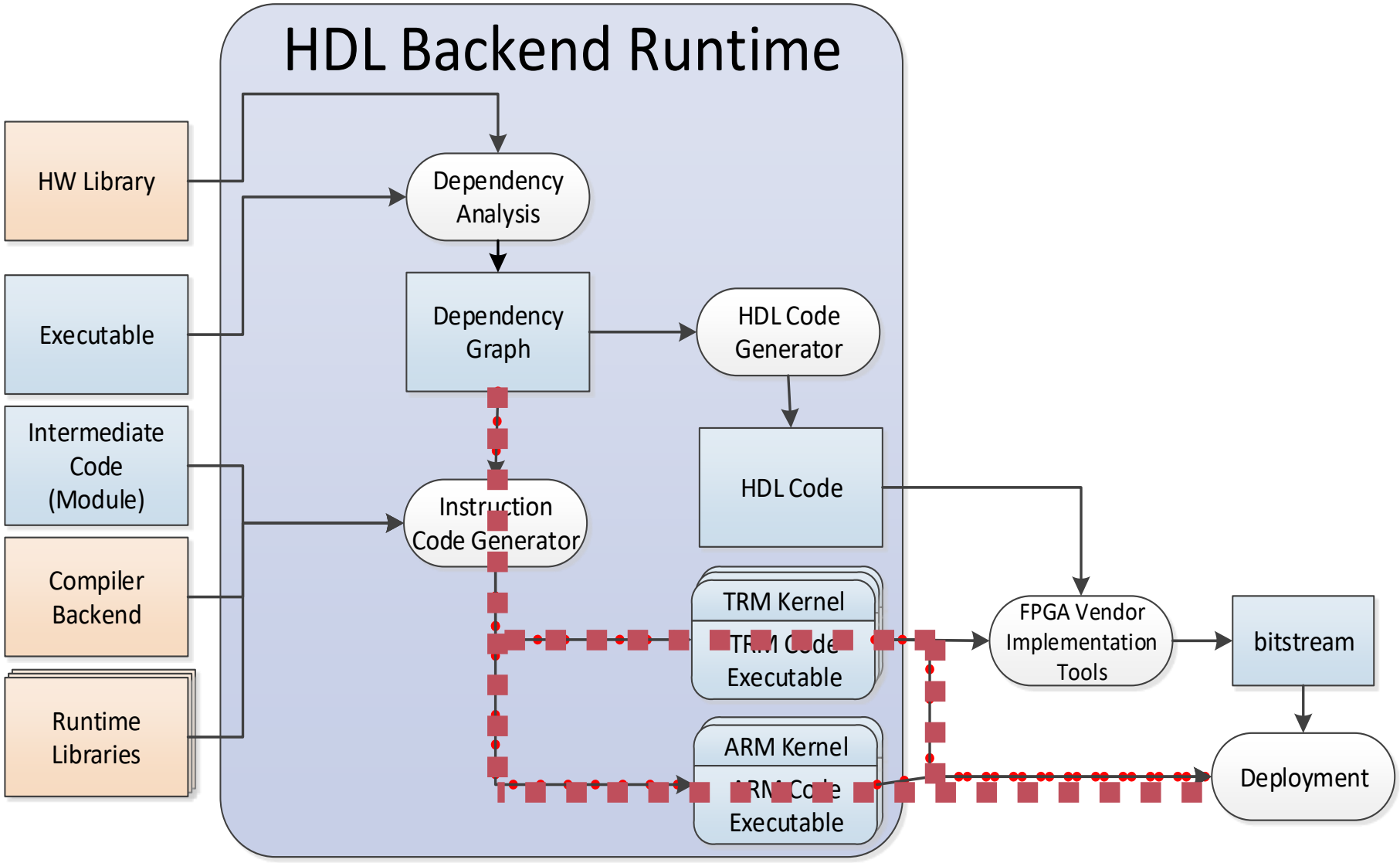


+ extensible
+ not redundant
+ simpler
+ simulation becomes execution

Frontend


Software Libraries
Source Code (Module)
Compiler Frontend
Intermediate Code (Module)
Compiler Backend
Executable
Simulation Runtime
Visualization Runtime
HDL Backend Runtime

Backend


HDL Backend Runtime
HW Library
Executable
Intermediate Code (Module)
Compiler Backend
Runtime Libraries
Dependency Analysis
Dependency Graph
Instruction Code Generator
HDL Code Generator
HDL Code
TRM Kernel
TRM Code Executable
ARM Kernel
ARM Code Executable
FPGA Vendor Implementation Tools
bitstream
Deployment

Extensibility: Defining components and platforms

Software HLL Code

```
type Gpo =
cell{Engine,DataWidth=32,InitState="0H"}
(input: port in);
```

Build Command

```
AcHdlBackend.Build
    --target="ZyboBoard"
    -p="Vivado"
    CRBM.TestCellnet ~
```

Component Specification

Platform Specification

Hardware HDL Code

```
module Gpo
#( parameter integer DW = 8 … )
(
input aclk, input aresetn , input [DW-1:0] …
);
```

Hardware Platform and Tools

Hardware Types

Platform Instances

Vendor specific tools

Component Specification

```
module Gpo;
import Hdl := AcHdlBackend;
var c: Hdl.Engine;
begin
    new(c,"Gpo","Gpo");
    c.SetDescription("General Purpose Output … ");

    c.SupportedOn("*"); (* portable *)

    c.NewProperty("DataWidth","DW",Hdl.NewInteger(32),Hdl.IntegerPropertyRangeCheck(1,Hdl.MaxInteger));
    c.NewProperty("InitState","InitState",Hdl.NewBinaryValue("0H"),nil);

    c.SetMainClockInput("aclk"); (* main component's clock *)
    c.SetMainResetInput("aresetn",Hdl.ActiveLow); (* active-low reset *)
    c.NewAxisPort("input","inp",Hdl.In,8);
    c.NewExternalHdlPort("gpo","gpo",Hdl.Out,8);

    c.NewDependency("aclk",true,false);

    c.AddPostParamSetterPortWidthFromProperty("inp","DW"));
    c.AddPostParamSetterWidthFromProperty("gpo","DW"));

    Hdl.hwLibrary.AddComponent
end Gpo.
```

Identification and description

Supported devices

Parameters

Ports

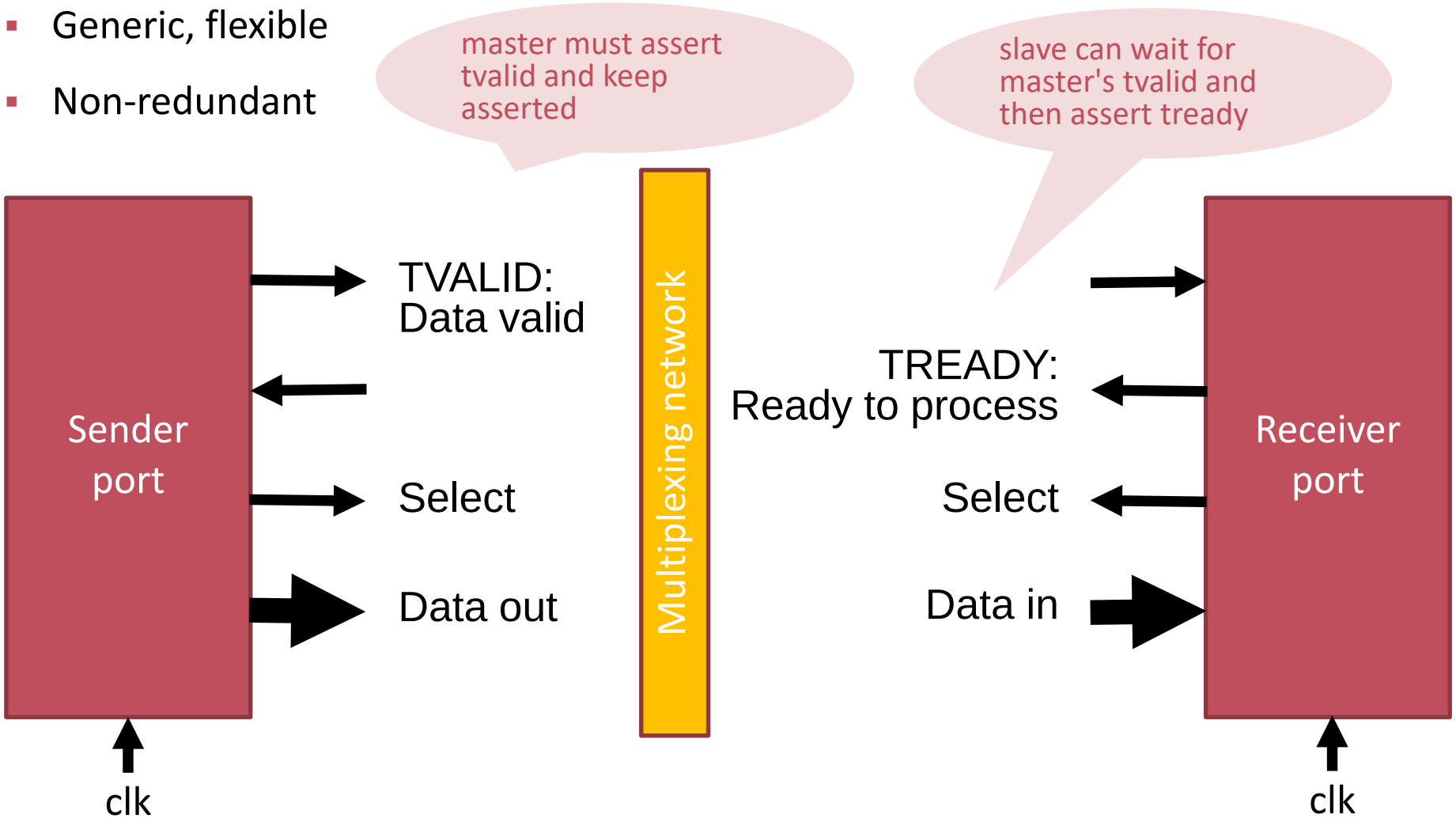
Dependencies

Configuration Actions

```
c.NewExternalHdlPort("gpo","gpo",Hdl.Out,8);
```

Generic Peer-to-Peer Communication Interface

- Use of **AXI4 Stream** interconnect standard from ARM
  - Generic, flexible
  - Non-redundant



Target Platform Specification

```
module Basys2Board;
import Hdl := AcHdlBackend, AcXilinx;
var  t: Hdl.TargetDevice;
     pldPart: AcXilinx.PldPart;
     ioSetup: Hdl.IoSetup;
     pin: Hdl.IoPin;
begin
     new(pldPart,"XC3S100E-4CP132");
     pldPart.SetJtagChainIndex(0);
     new(t,"Basys2Board",pldPart);

     new(pin,Hdl.In,"B8","LVCMOS33");
     t.NewExternalClock(pin,50000000,50,0); (* ExternalClock0 *)
     t.SetSystemClock(t.clocks.GetClockByName("ExternalClock0"),1,1);
     new(pin,Hdl.In,"G12","LVCMOS33");
     t.SetSystemReset(pin,true);

     new(ioSetup,"Gpo_0");
     ioSetup.NewIoPort("gpo",Hdl.Out,"U16,E19,U19,V19","LVCMOS33");
     t.AddIoSetup(i
     Hdl.hwLibrary.Ad
end Basys2Board.
```

FPGA Part

System Signals

Mapping of external Ports

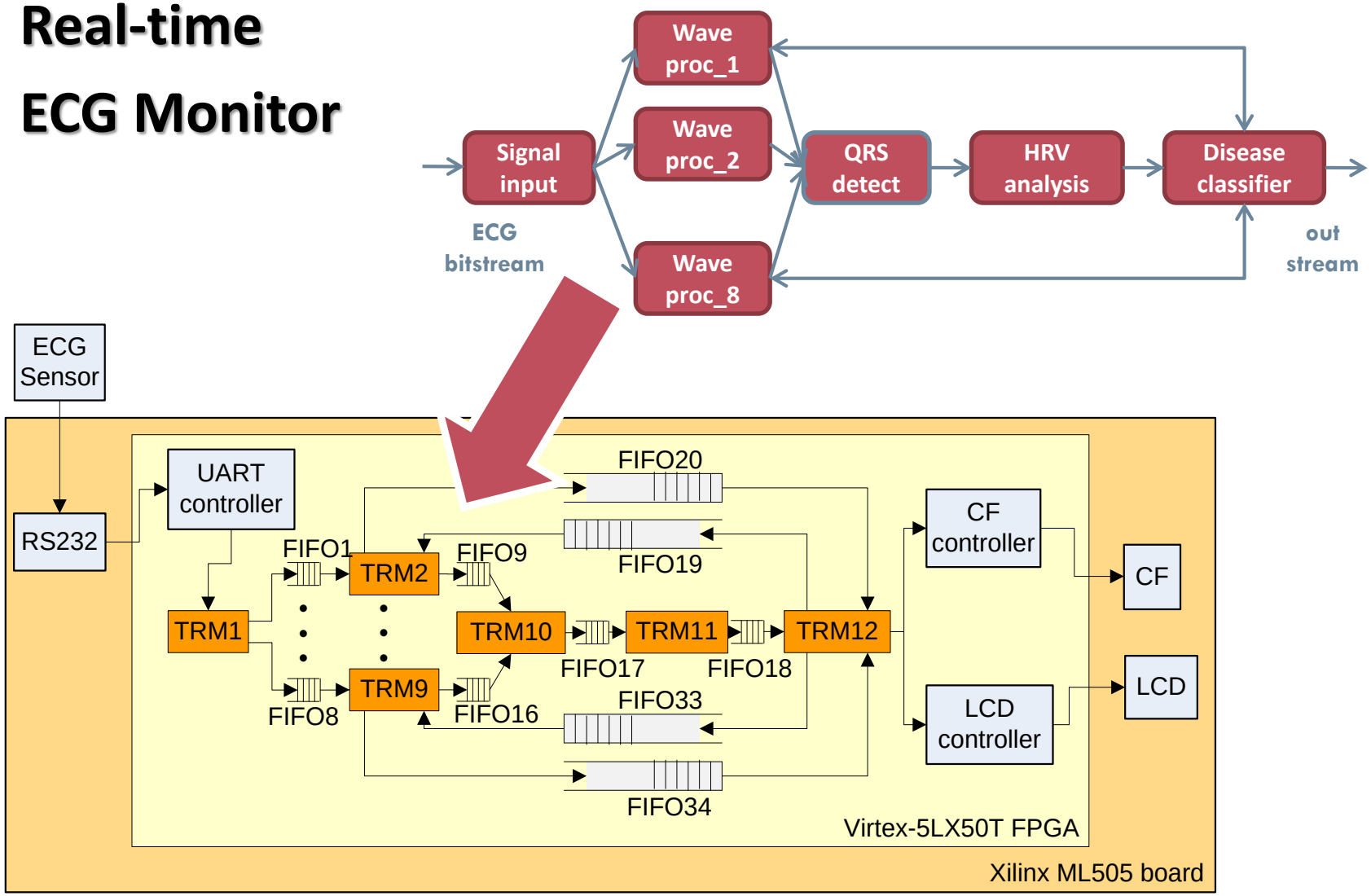
```
ioSetup.NewIoPort("gpo",Hdl.Out,"U16,E19,U19,V19","LVCMOS33");
```

Case Study 1: ECG

Focus: Resources and Power

Real-time

ECG Monitor



Resources

- ECG Monitor*

#TRMs	#LUTs	#BRAMs	#DSPs	TRM load
12	13859 (48%)	52 (86%)	12 (25%)	<5% @116 MHz

- Maximum number of TRMs in communication chain

FPGA	#TRMs	#LUTs	#BRAMs	#DSPs
Virtex-5	30	27692 (96%)	60 (100%)	30 (62%)
Virtex 6	500			

*8 physical channels @ 500 Hz sampling frequency implemented on Virtex 5

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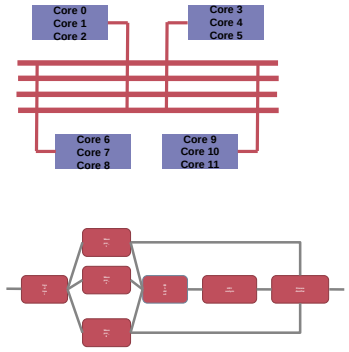
Comparative Power Usage

- Preconfigured FPGA (#TRMs, IM/DM, I/O, Interconnect fixed) versus fully configurable FPGA (Active Cells)

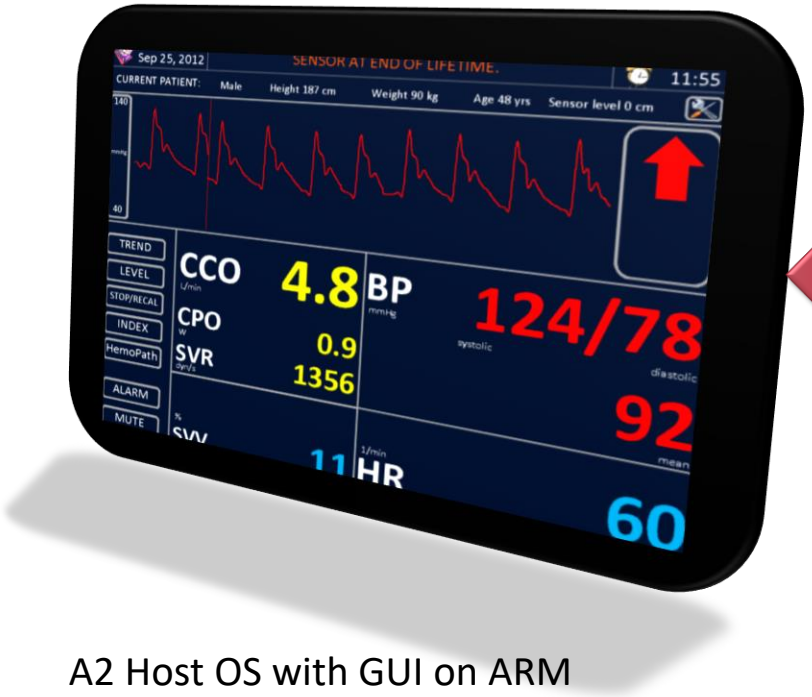


System	Static Power (W)	Dynamic Power (W)
Preconfigured ("TRM12")	**3.44**	**0.59**
Dynamically configured	**0.5**	**0.58**

86% saving!

Case Study: Non-Invasive Continuous Blood Pressure Monitor

Focus: Development Cycle Time

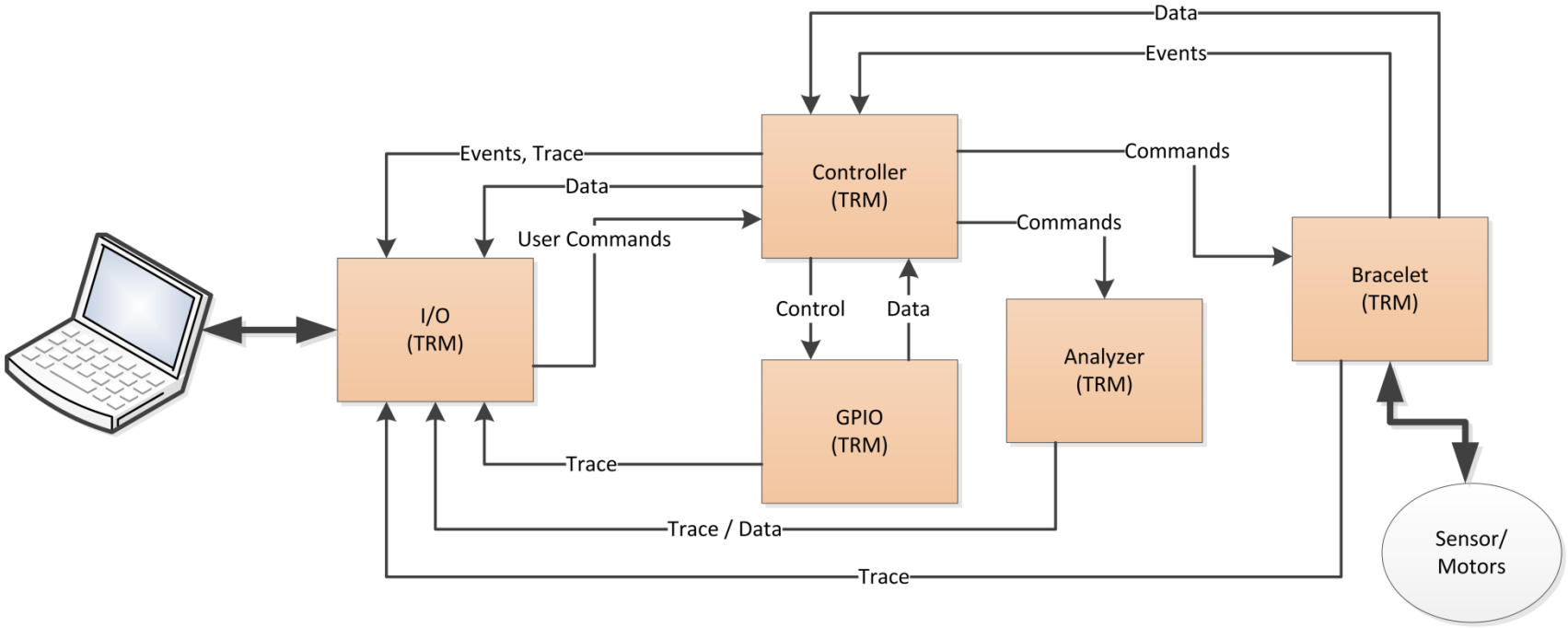


A2 Host OS with GUI on ARM

Sensor control and medical algorithms on Zynq PL

Sensors and Motors on Bracelet

Medical Monitor Network On Chip



Dominated by TRM processors. Feedback driven. Not performance critical.

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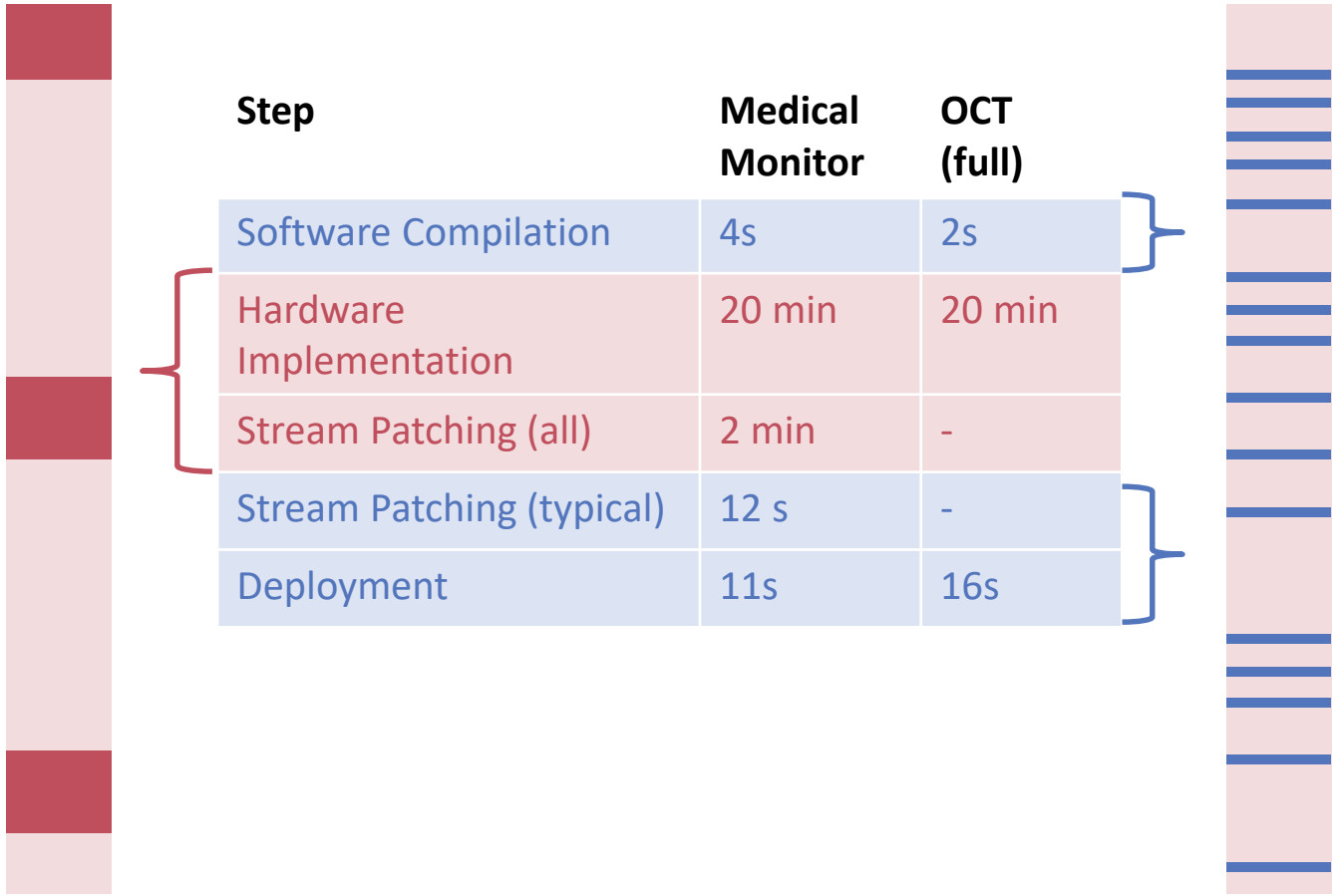
Development Cycle Times



Step	Medical Monitor	OCT (full)
Software Compilation	4s	2s
Hardware Implementation	20 min	20 min
Stream Patching (all)	2 min	-
Stream Patching (typical)	12 s	-
Deployment	11s	16s

sporadic

often

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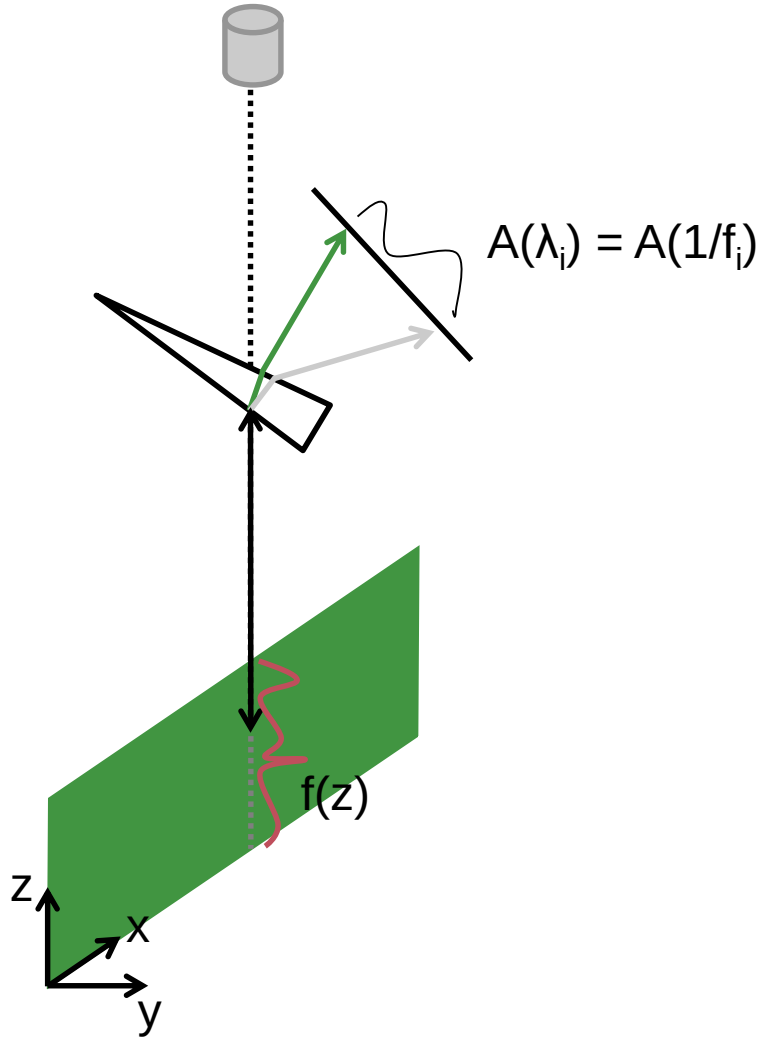
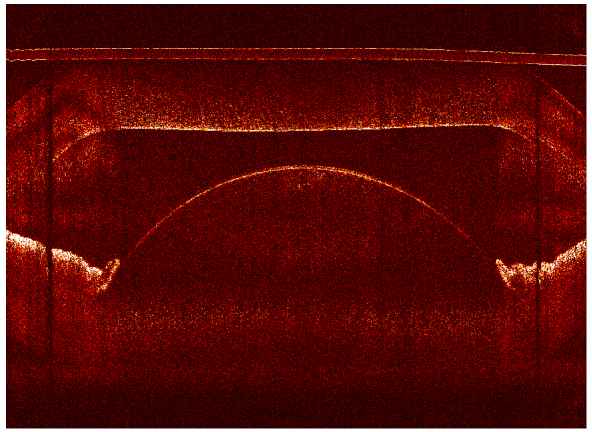
Case Study 3: Optical Coherence Tomography

Focus: Performance





z-Axis Processing

1. Non uniform sampling

   $A(\lambda_i) \rightarrow \tilde{A}(f_i)$

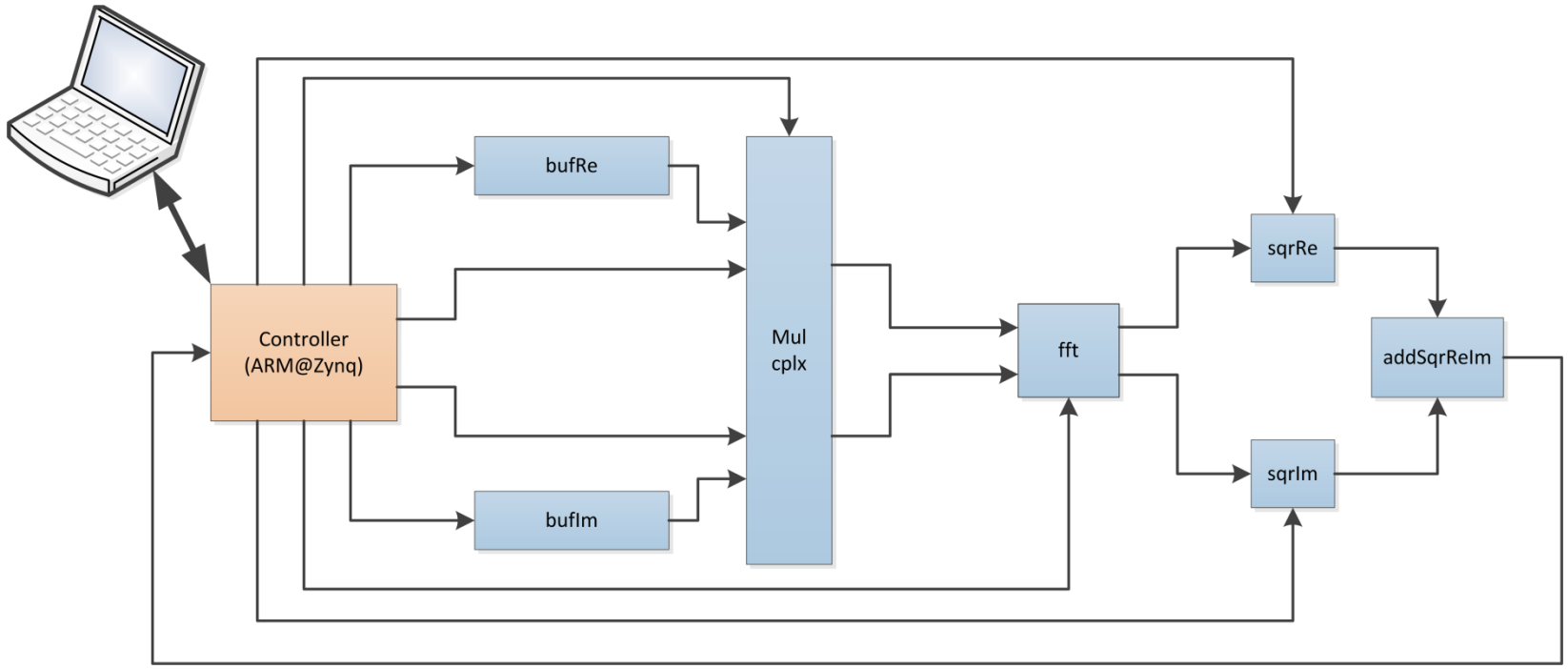
2. Dispersion compensation

3. (Inverse) FFT

… for many lines x in a row (2d)
… and many rows y in a column (3d)

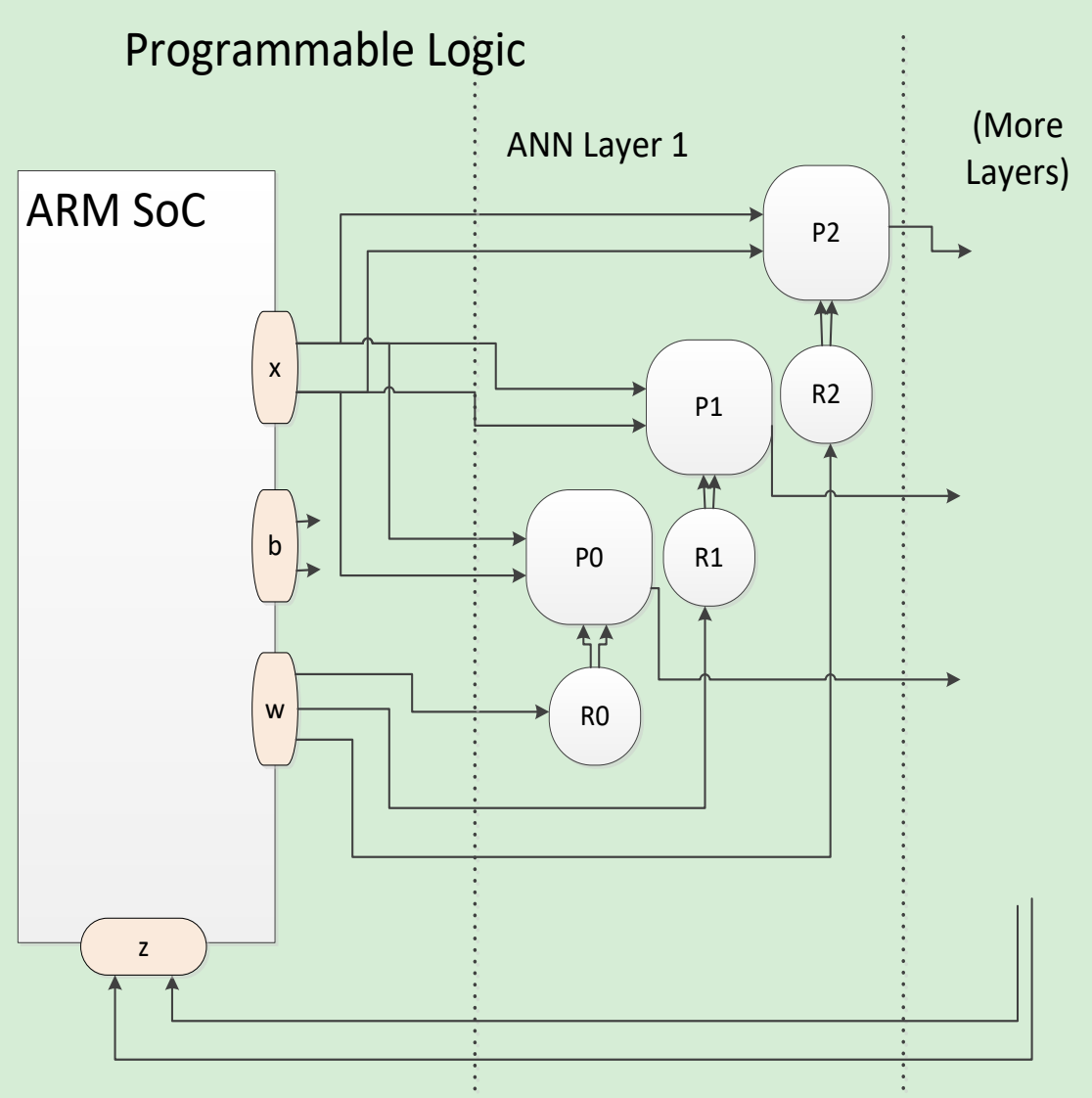
A component of OCT image processing

Dispersion Compensation

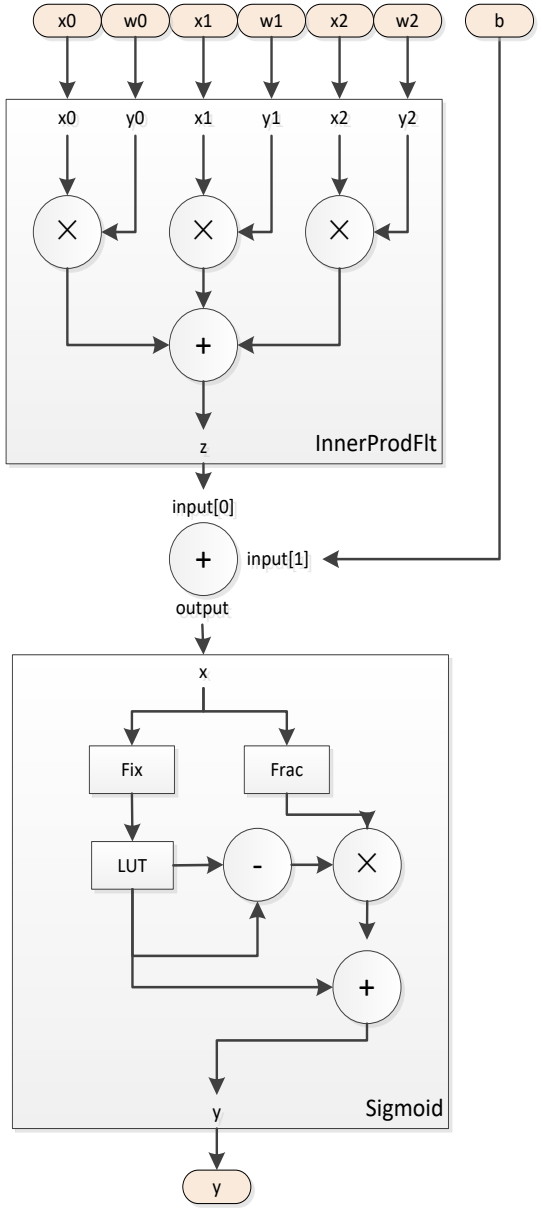


Dominated by Engines. Dataflow driven.

Case Study: ANN



Perceptron



Performance and Resource Usage

	Medical Monitor	**Simple OCT**	**OCT**	**Perceptron**
Architecture	Spartan 6 XC6SLX75	Zynq 7000 XC7Z020	Zynq 7000 XC7Z020	Zynq 7000 XC7Z010
Resources	28% Slice LUTs, 4% Slice Registers 80% BRAMs 24% DSPs	11% Slice LUTs, 6% Slice Registers 7% BRAMs 15% DSPs 1 ARM Cortex A9	17% Slice LUTS 8% Slice Registers 22% BRAMs 31% DSPs 1 ARM Cortex A9	83% Slice LUTS, 67% Slice Registers 13.33% BRAMs, 21% DSP 1 ARM Cortex A9
Clock Rate	58 MHz	118 MHz	50 MHz	147 MHz
Data Bandwidth	1.25 Mbit /s (in) 23 kB/s (out)	236 MWords/s (in) 118 MWords/s (out)	50 MWords/s (in) 50 MWords/s (out)	9.6 GBits/s in 9.6 GBits/s out
Performance	**--**	**8.3 GFPOps* up to 32 GFPops****	**4.3 GFPOps***	**4.9 GFlops**
Power	**~2W**	**~5W**	**~5W**	**2.1 W**

** Fixed point operations, 32bit
* when instantiated 4 times

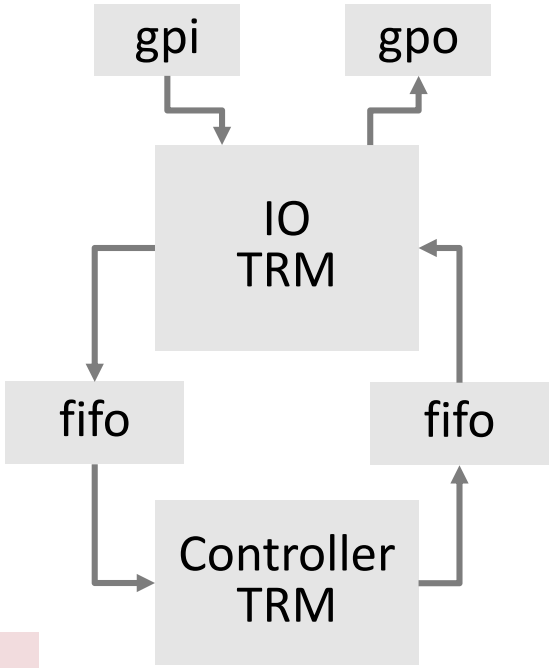
Conclusion

ActiveCells: Computing model and tool-chain for configurable computing

- Configurable interconnect → Simple Computing, Power Saving
- Embedding of task engines → High Performance
- Hybrid compilation→ Quick Development
- Backend execution → Eased Flexibility and Extensibility

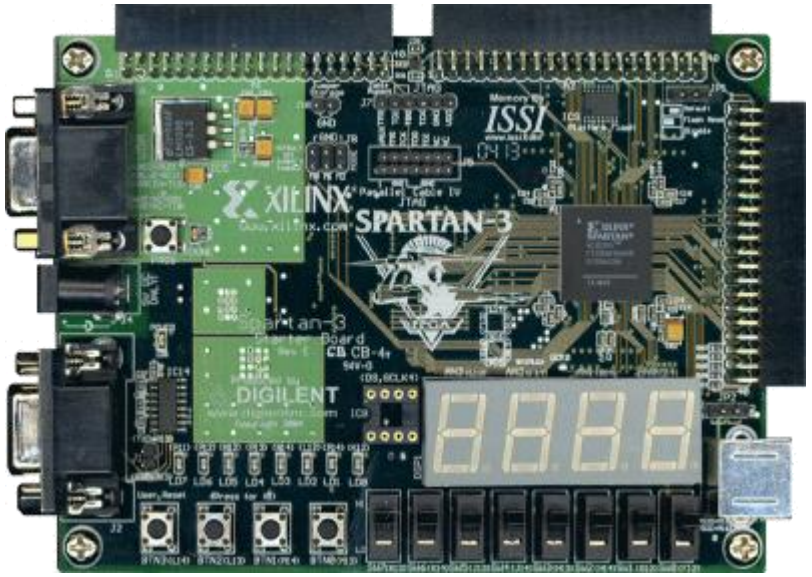
Mapping to Hardware – Simple Example

```
IO*=CELL (input: PORT IN; output: PORT OUT;
          buttons: PORT IN; leds: PORT OUT);
BEGIN ...
END IO;

Controller*=CELL (input: PORT IN; output: PORT OUT)
BEGIN ...
END Controller;

VAR controller: Controller; io: IO;
     gpo{DataWidth=8}: Engines.Gpo;
     gpi{DataWidth=11}: Engines.Gpi;
BEGIN
   NEW(controller);  NEW(io);
   NEW(gpi); NEW(gpo);

   CONNECT (controller.output, io.input, 32);
   CONNECT (io.output, controller.input, 32);
   CONNECT (gpi.output, io.buttons);
   CONNECT (io.leds, gpo.input);
END Simple.
```



→ Blackboard / Code inspection

Spartan3 Board



Resources

4-input LUTS	3840
Flip Flops	3840
BRAMs	12
DSPs	-

Resource Usage Scenarios

1 TRM

```
CELLNET Game;

IMPORT LED;

TYPE

IO*=CELL {DataMemorySize(512),
CodeMemorySize(1024), LED} (in: PORT
IN);
BEGIN
END IO;

VAR  io: IO;
BEGIN
   NEW(io);
END Game.
```

Resources

4-input LUTS	27%
Flip Flops	5%
BRAMs	16%

TRM →TRM

```
VAR  io: IO; trm: TRM;
BEGIN
NEW(io); NEW(trm);
   CONNECT(trm.out, io.in);
END Game.
```

Resources

4-input LUTS	58%
Flip Flops	9%
BRAMs	33%

TRM ← →TRM -> TRM

(cf. next page)

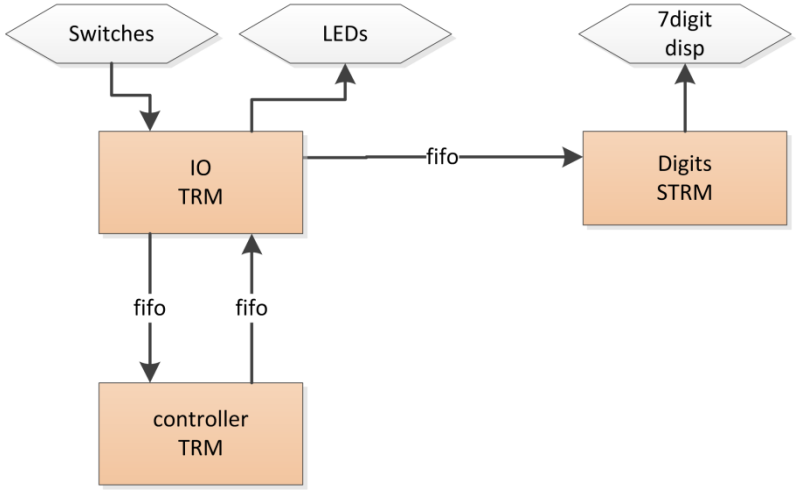
Resources

4-input LUTS	86%
Flip Flops	18%
BRAMs	75%

➔ TRM ≈ 21-27% (LUTs), 16% (BRAMs); Fifo ≈6% (LUTs)

Resource Usage (Lab)

```
controller: Controller;
ioTRM: IO;
digitsDriver: DigitsDriver;
digits: Engines.LEDDigits;
gpo{DataWidth=8}: Engines.Gpo;
gpi{DataWidth=11}: Engines.Gpi;

BEGIN
NEW(controller);
NEW(ioTRM);
NEW(digitsDriver);
NEW(digits);NEW(gpi);NEW(gpo);
CONNECT( controller.cmdOUT,ioTRM.cmdIN,10);
CONNECT( ioTRM.cmdOUT,controller.cmdIN,10);
CONNECT( gpi.output,   ioTRM.ButtonsIN);
CONNECT( ioTRM.LEDOUT, gpo.input);
CONNECT(ioTRM.digitsOUT, digitsDriver.cmdIN,10);
CONNECT(digitsDriver.ledOUT, digits.input);
```



- 3 TRMs
- 3 FIFOs

Resources

4-input LUTS	86%
Flip Flops	18%
BRAMs	75%