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Redesigning the Computer for Security

Using Haskell EDSLs to Bootstrap a New Computing Platform

DARPA CRASH SAFE
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State of Computer Security

- How secure is our critical infrastructure?

```
Welcome to wellhead7.pipelines-and-things.com
username: admin
password: admin
```

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The SAFE Solution to Security

- What if we could start from a clean slate?
- SAFE is a Codesign of…
  - A new applications programming language (Breeze).
  - A new system programming languages (Tempest).
  - A new operating system.
  - A new processor .
  - With security at every level for defense in depth.
- Why hardware enforced security?
  - Dynamic security checking is too expensive in software.
    - Fine grained information flow control (IFC).
  - Covers the most general attack model.
    - Scripting attacks down to machine code injection.

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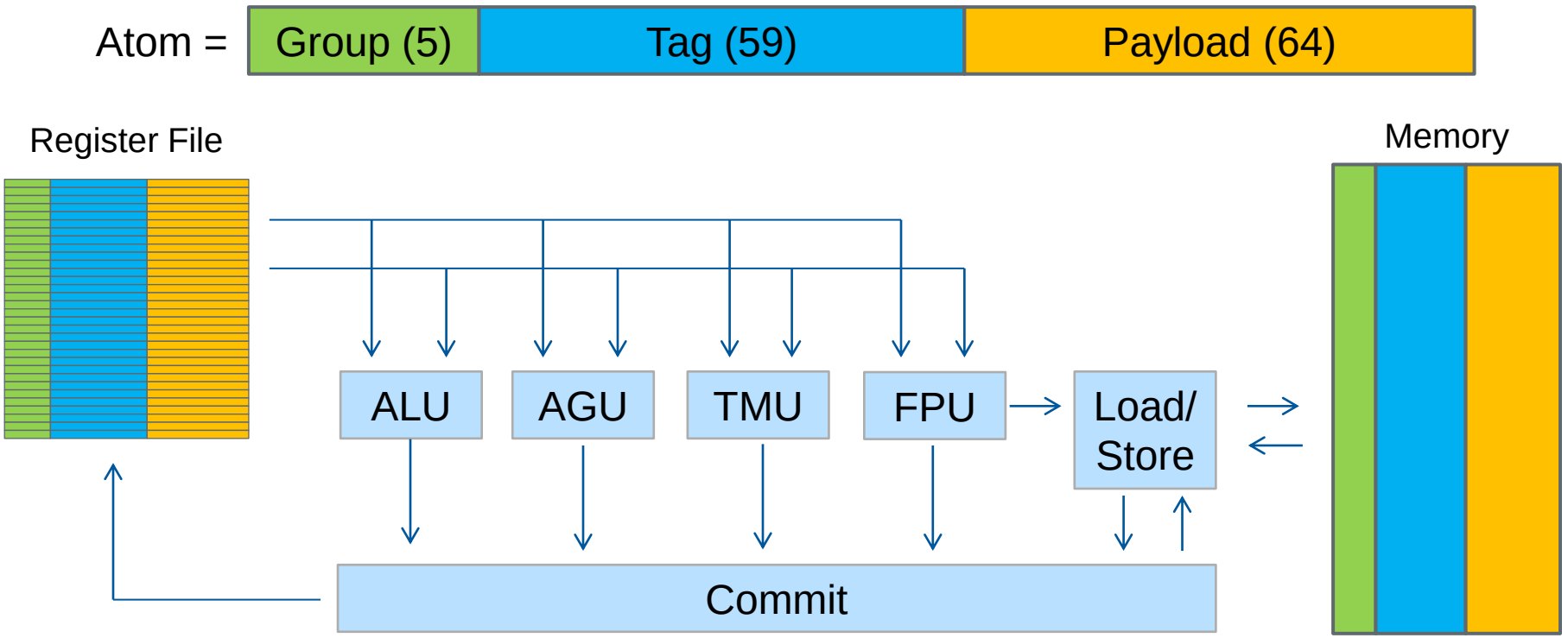
SAFE Hardware Architecture



- Atomic group unit (AGU) checks atom types, i.e. instructions, data, pointers, streams, etc.
- Fat pointer unit (FPU) check pointer operations.
- Tag management unit (TMU) checks and applies tags.

Starting Project at Day 1

- We have an outline for an ISA, but nothing else.
  - TIARA project as a baseline (Howard Shrobe, Andre DeHon, Thomas Knight).
  - But no languages, no toolchain, no hardware.
- How to proceed?
  - Sketch out an assembly language.
  - Build an instruction set simulator.
  - Start writing and simulating small assembly programs.
  - HW researchers start coding Bluespec.
  - PL researchers start designing Breeze.
    - Plan is to steal Andrew Meyers work on Jif. Port ideas to a dynamic PL.
      - “Breeze should be done in a couple of months.”

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SAFE Assembly

Frames to manage fat pointer bounds.

Atomic group declarations on data.

Tags on data.

Gate structures for secure closures.

- How long can we keep this up?

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At Year 1.0

- Assembly is tedious. We need macros.
- Breeze interpreter running. Pressure to start building the compiler.
- Solution: A SAFE assembly DSL embedded in Haskell.
  - Use Haskell is a macro language.
  - Becomes a library for the Breeze compiler.
- Breeze Language, Version 7
  - 4-5 weeks spent on figuring out datatypes for Booleans.
    - “Hmm, this IFC stuff is kind of tricky.”
  - Difficulties arise with access control.
    - Convenience and modularity of lexical authority passing and one-principal-per-module is anything but.

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SAFE Assembly in Haskell

```
testOffpCode :: Integer -> Program a Label
testOffpCode frameSize = do
  -- frame of values
  valFrame <- frame "Frame of values" $ do
    space frameSize

  -- code frame
  frame "Code frame" $ do

    integer' 0 R0
    integer' 1 R1
    framePointer' valFrame Nothing R2
    testgrp R2 R3 FramePointer
    while R3 $ do
        offp R1 R2 R2
        add R1 R0 R0
        testgrp R2 R3 FramePointer

    integer' frameSize R1
    compareAtoms R5 R1 R0 R6
    ifThenElse R6
      (recordSuccess "done offp")
      (recordFailure "done offp")
    jumpToPassOrFail
```

A Monad to capture programs.

Macros for setting up data.

Macros for better control flow.

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At Year 1.5

- As a EDSL, Haskell makes for great macros, but it's still assembly.
  - Manual register allocation, calling conventions, and data structures.
- Meanwhile, Breeze compiler inches off ground, but…
  - Awkward transition from high level CPS IR to assembly.
    - We really need an IR somewhere in between.
  - On plus side, SAFE EDSL worked great in code generator.
- Breeze Language, Version 12
  - "What do we do on an access violation?"
  - "Simple. We stop the machine."
  - "But what if I maliciously send you data you can't access?"
  - "Simple, I'll just check the label before I attempt to read it."
  - "But what if the label itself is private?"
  - "Oh..."
    - The Poison Pill problem.

At Year 2.0

- Breeze compiler goes through major overhaul.
  - Some improvement to middle IRs, but still not enough.
  - Breeze compiler is temporarily shelved.
    - Breeze won't come to the rescue of the OS.
  - We REALLY need a higher low-level language.
- Breeze Language, Version 23
  - "We have a solution to poison pills. We'll make all labels public."
    - To label data you must specify the label in advance (brackets).
      - Prevents labels from being information channels.
    - But public labels are not compatible with lexical authority passing.
      - The lexical authority containment problem.
      - Breeze switches to dynamic authority.

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At Year 2.5

- Tempest is started: The systems programming language for SAFE.
  - Imperative with automatic register allocation and optimizations.
  - Control of assembly with inlining and user specified calling conventions.
  - Uses the SAFE EDSL as a backend.
  - As and EDSL, nicely fills the Breeze compiler IR gap.
- Breeze Language, Version 34
  - Delayed exceptions with not-a-value values (NaVs).
  - Dynamic authority is replaced with clearance.
    - Similar ideas. Both work with public labels.

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Tempest EDSL with Inline Assembly

```
(/-/) :: (ToExpr e1, ToExpr e2) => e1 -> e2 -> Expr
a /-/ b = block $ do
  a <- var a
  b <- var b
  return $ asm [intT] $ \ result -> beginAsm $ do
    sub (R a) (R b) (R result)

(/</) :: (ToExpr e1, ToExpr e2) => e1 -> e2 -> Expr
a /</ b = block $ do
  true  <- var 1
  false <- var 0
  diff  <- var $ a /-/ b
  return $ asm [intT] $ \ result -> beginAsm $ do
    trueCase <- label
    end      <- label
    bneg (R diff) trueCase
    mvrr (R false) (R result)
    jmp end
    trueCase -: do
      mvrr (R true) (R result)
    end -: do
      nop
```

SAFE Assembly Sublanguage

The SAFE Flow

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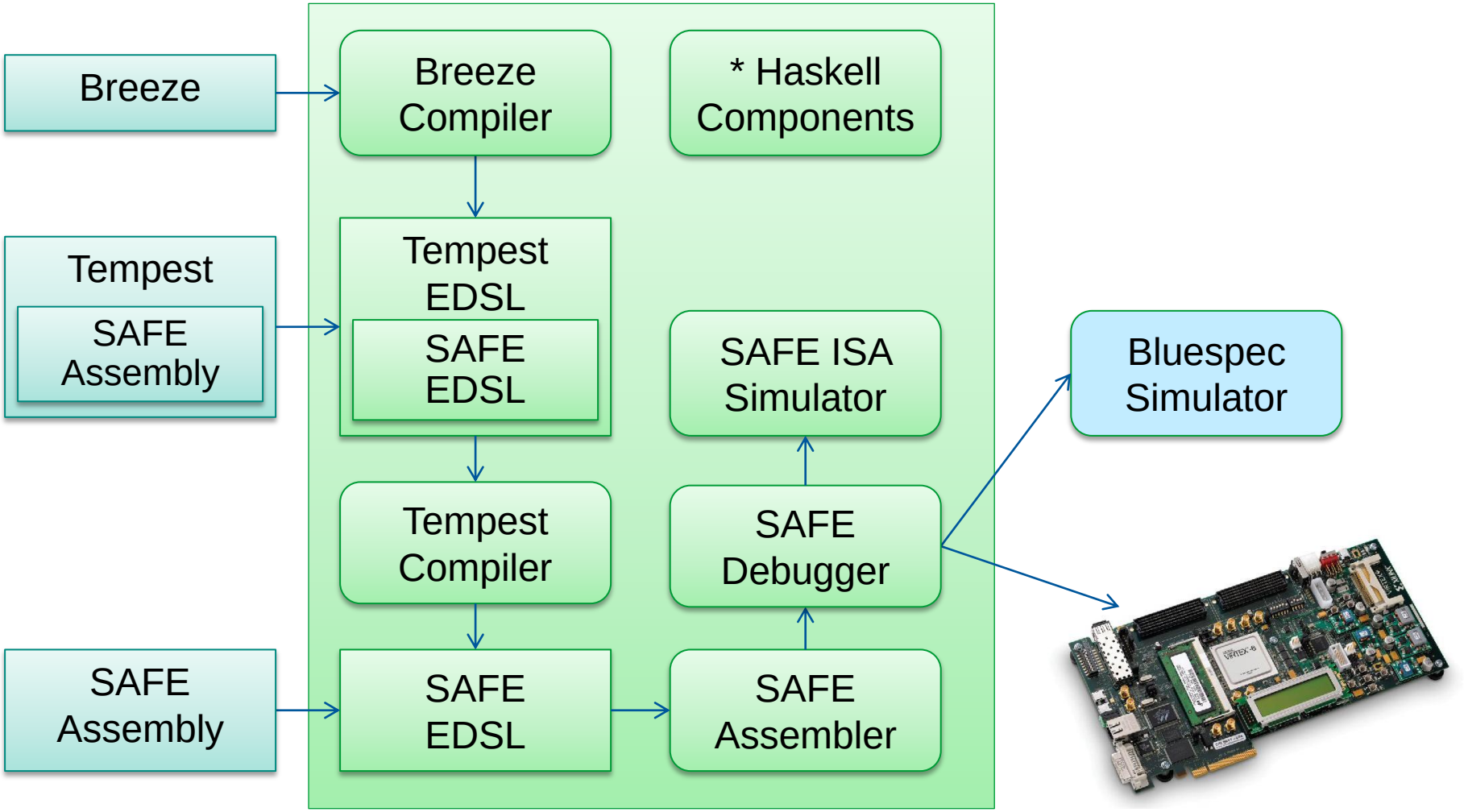

Lessons Learned (1)

- Designing a higher order IFC language is very hard.
  - Optimal number of PL researchers on a project: 2 to 7
- On day 1, we should have started Tempest, not assembly.
  - Hard to achieve good productivity with assembly code.
  - Tempest is the right level for runtime / processor codesign.
    - The level of indirection provides insulation from a changing ISA.
- EDSLs are great for bootstraping a language.
  - And make excellent backend libraries!

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Lessons Learned (2)

- EDSLs require that engineers are comfortable with the host language.
- EDSLs are hard to debug.
- Still good reasons for concrete syntax.
  - More relevant for some languages than others.
    - Tempest vs. SAFE assembly.
  - When is the best transition point?
    - Early pressure from developers for modular programming.
    - One language has modularity, the switch can be made.
- Would a DSL have helped hardware design?
  - Forever debugging ISS and FPGA.
  - A DSL describing ISA semantics could keep it synchronized.
    - Generating Bluespec, ISS, SAFE EDSL, Coq, and Documentation.

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Final Plugs

- SAFE has produced a volume of interesting papers.
  - Private vs. public labels.
  - Lexical authority vs. dynamic authority vs. clearance.
  - Exception handling in IFC.
  - Efficient tag processing in hardware.
  - Efficient fat pointer encoding.
  - See: http://www.crash-safe.org/papers
- At ICFP this week: "Testing Noninterference, Quickly"
  - Catalin Hritcu, John Hughes, Benjamin C. Pierce, Antal Spector-Zabusky, Dimitrios Vytiniotis, Arthur Azevedo de Amorim and Leonidas Lampropoulos.
  - Using QuickCheck to test ISA security.
- We're Hiring!
  - Needed: Functional compiler engineers for Breeze and Tempest.

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Thanks!

http://crash-safe.org/

The SAFE Team:
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