Programatica Tools
for
Certifiable, Auditable Development
of
High Assurance Systems
in
Haskell

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Flashback to HCSS in 2001:

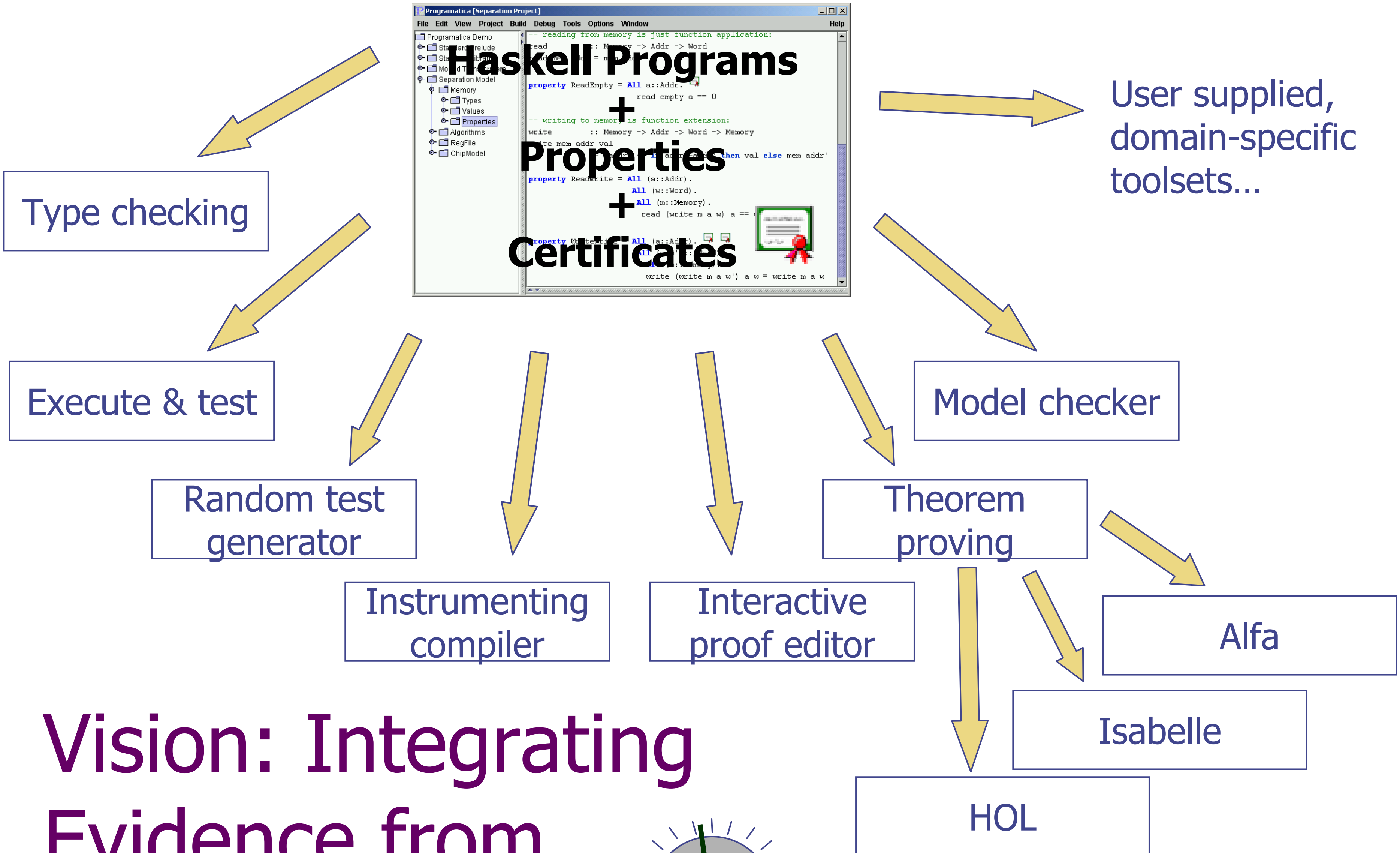
- We had assembled a team …
- … but the Programatica Project had not officially started …
- I presented our vision of what Programatica might become …

The Programatica Vision:

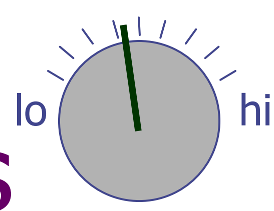
- Build a program development environment that supports and encourages its users in thinking about, stating, and validating key properties.

- Enable programming and validation to proceed hand in hand, using properties to link the two.

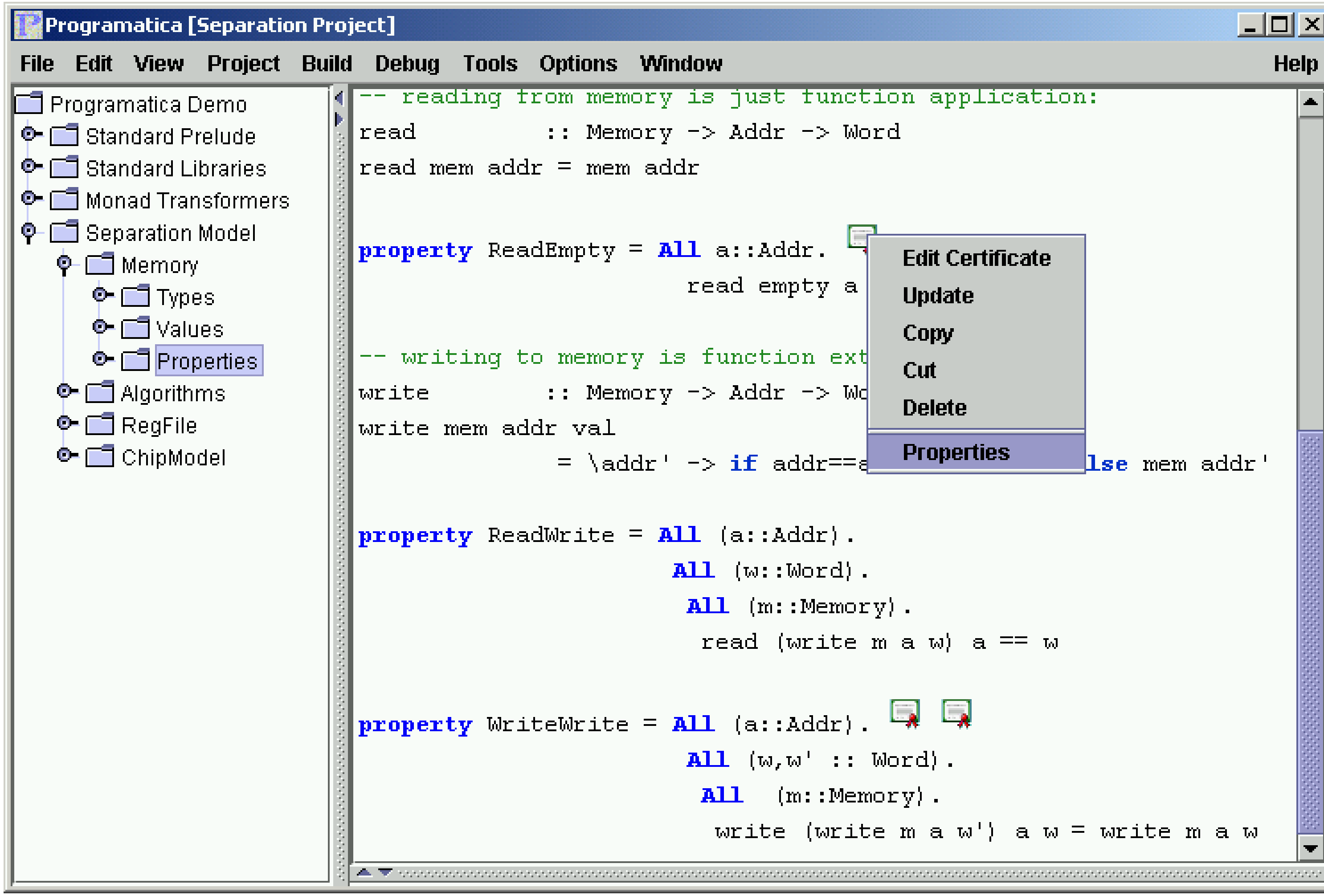
- Allow users to realize benefits gradually by choosing between varying levels of assurance.



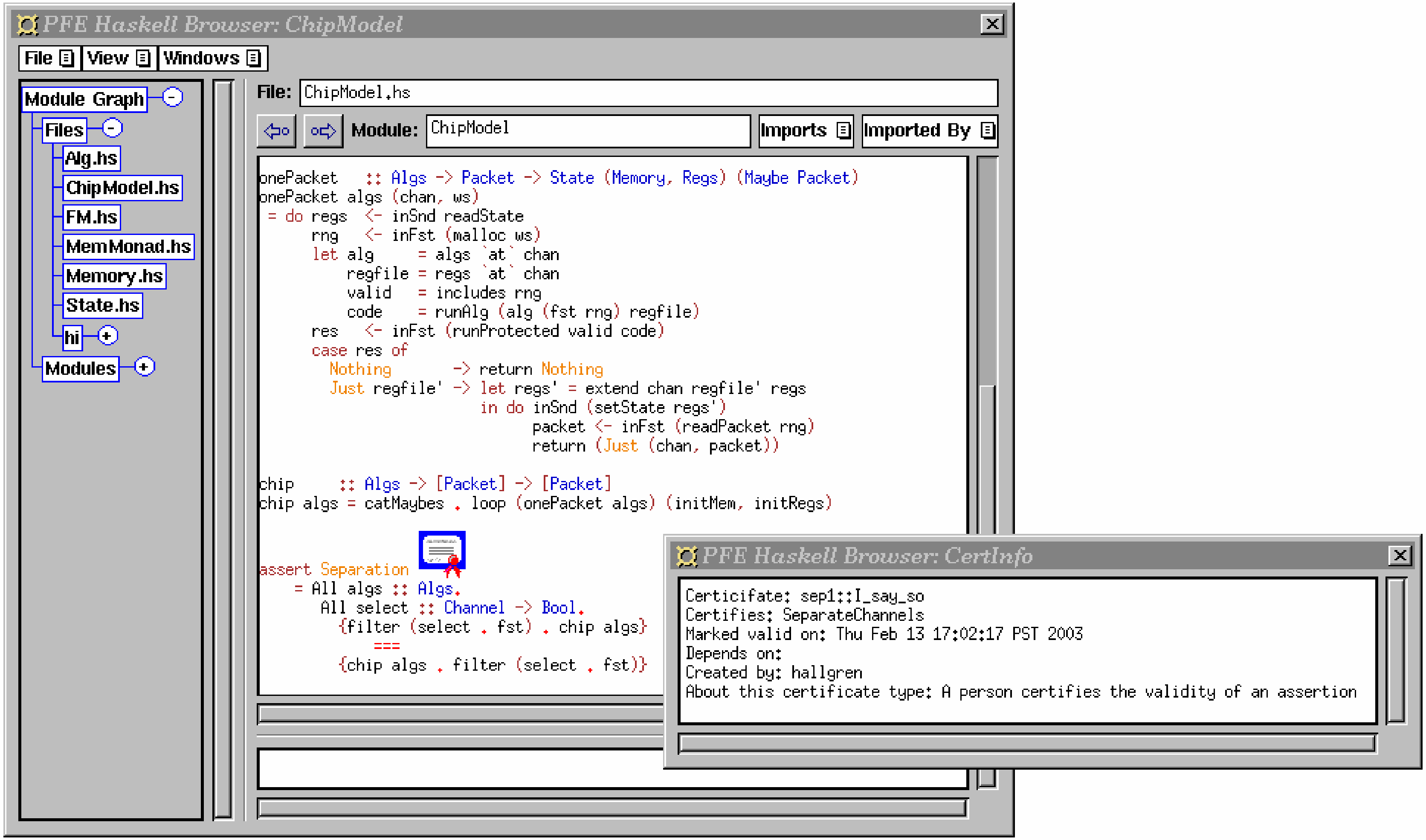
Vision: Integrating Evidence from Multiple Sources



Back then: Mockups



Today: Real, Working Tools



Back then: A view from 2020

- In it’s time, Programatica was the most sophisticated program development environment on the market;

- “It scares me to think that we nearly ended up in a world dominated by Java technology … Programatica was a godsend; we couldn’t have made the transition to Haskell without it …”

James Gosling, Microsoft CEO, eComdex 2007

Today: The view from 2003

- We’re on track to have a public release of the tools early in the summer …

- We’re preparing materials for a short course on the Programatica approach to software development, and on the toolset, to coincide with the release …

Building High-assurance Software:

There are many ways to increase assurance:

- Test programs on specific cases
- Test programs on randomly generated test cases derived from expected properties
- Peer review
- Use algorithms from published papers
- Reason about equational properties
- Reason about meta-properties (e.g., using types)
- Use theorem provers to validate (translated) code
- …

Each one can contribute significantly to increased reliability, security, and trustworthiness

Evidence: A Unifying Feature

- There are significant differences in the applicability, assurance, and technical details of each of these techniques.

- But there is a common feature:
  - Each one results in some **tangible** form of **evidence** that provides a **basis for trust**

Examples of Evidence:

There are many kinds of evidence:

- An (input, expected output) pair for a test case
- A property statement, and heuristics for guiding the selection of "interesting" random test cases
- A record of a code review meeting
- A citation/URL for a published paper or result
- An equational proof
- A type and the associated derived property
- A translation of the source program into a suitable theory and a user-specified proof tactic
- …

In Programatica, each different kind of evidence is stored with the program as a **certificate**

Evidence and Certificates:

The certificate abstraction is designed to support:

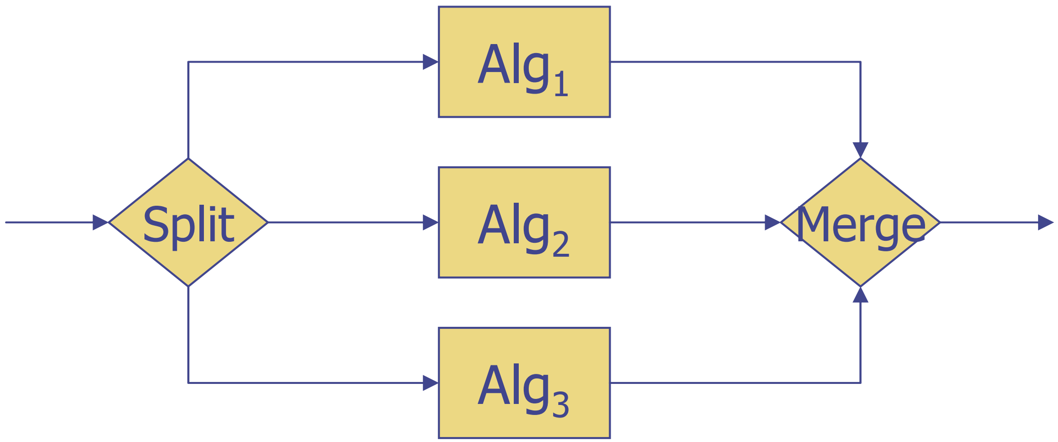
- **Capture** of evidence of validity (in many different forms) and **Collation** with source materials
- **Combination** of evidence
- **Tracking** dependencies and **detecting** when evidence needs to be revalidated because of changes in the source code
- **Management** of evidence by analyzing and reporting on what has been established, identifying weaknesses, guiding further effort, etc…

Programatica Components:

- A semantically rich, formal modeling language (Haskell)
- An expressive programming logic that can be used to capture critical program properties (P-logic)
- A toolset for creating, maintaining, and auditing the supporting evidence (pfe,cert,…)

Example: Modeling a Crypto-Chip

- An example based (very loosely) on the General Dynamics AIM crypto-chip
- Conceptual view:



- One chip, multiple channels
- Channels may use different algorithms
- GUARANTEED separation between channels

High-level Model:

```
chip :: Algs → ([Packet]→ [Packet])
```

Map channels to algorithms

Packet Filter

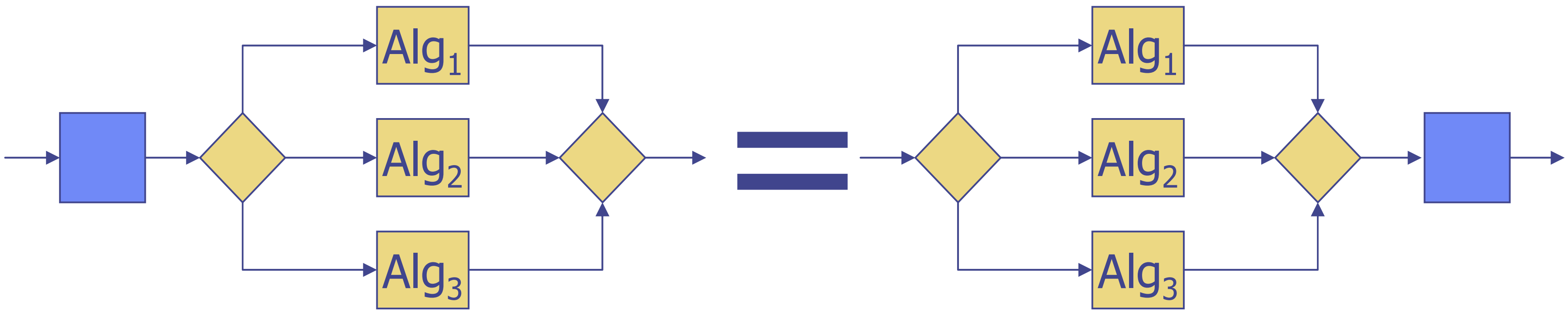
```
type Packet = (ChannelId, Payload)
```

Channel Id

Data

The Separation Property:

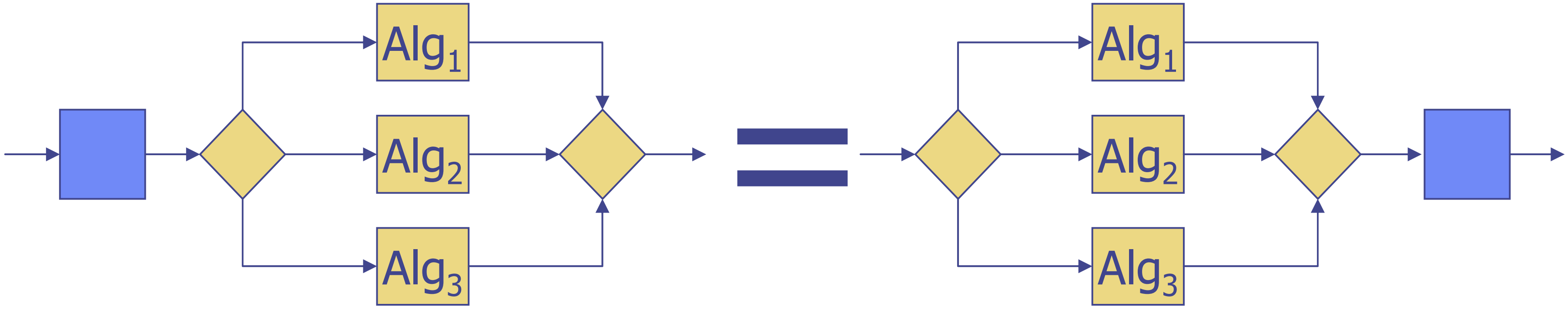
```
assert Separation =
 All algs :: Algs.
  All select :: (ChannelId → Bool).
    { filter (select . fst) . chip algs }
         ===
    { chip algs . filter (select . fst) }
```



The Separation Property:

This law guarantees that:

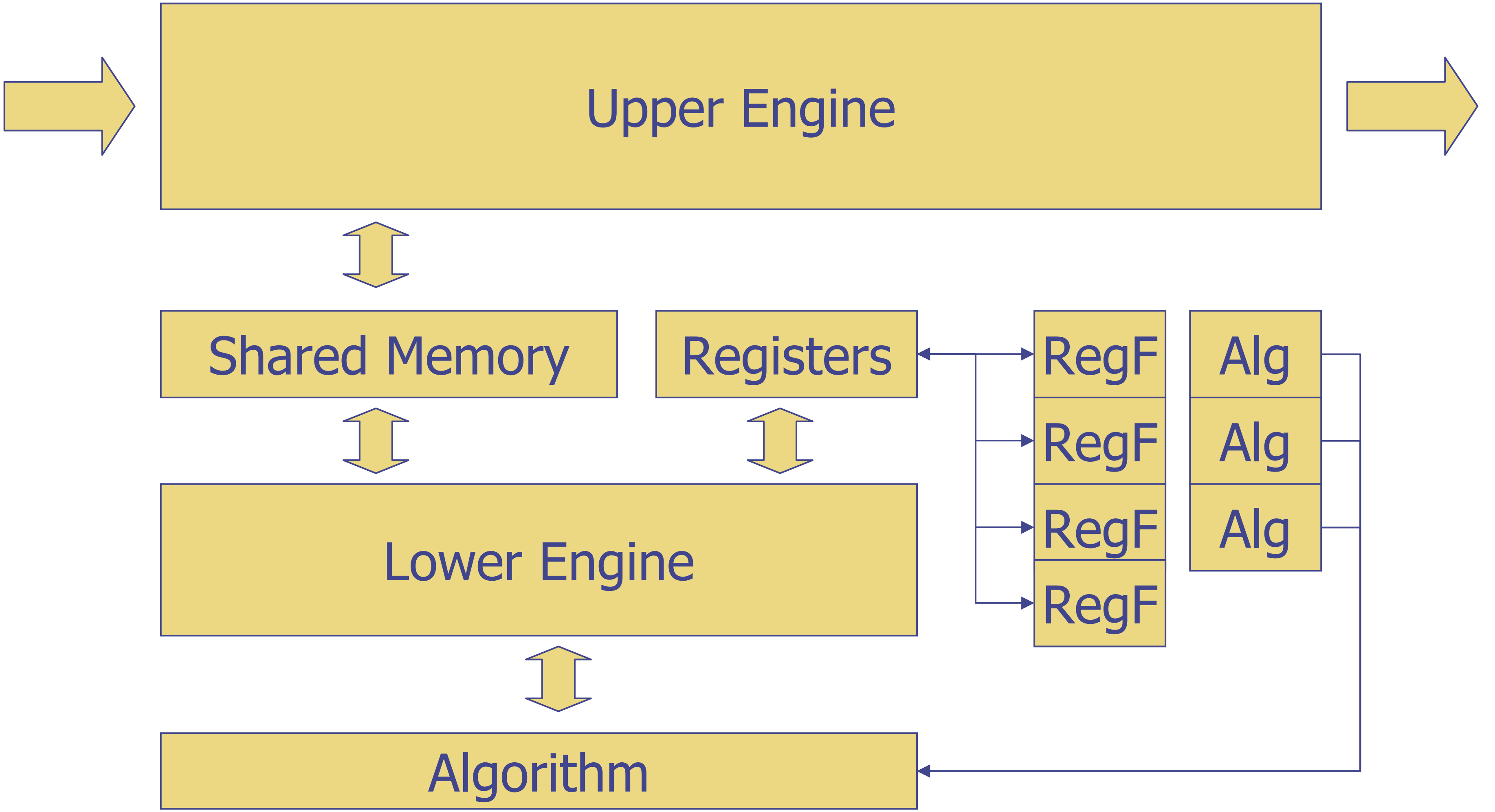
- Outputs do not depend on inputs to other channels.
- Channels do not generate spurious outputs.



Putting Programatica to Work:

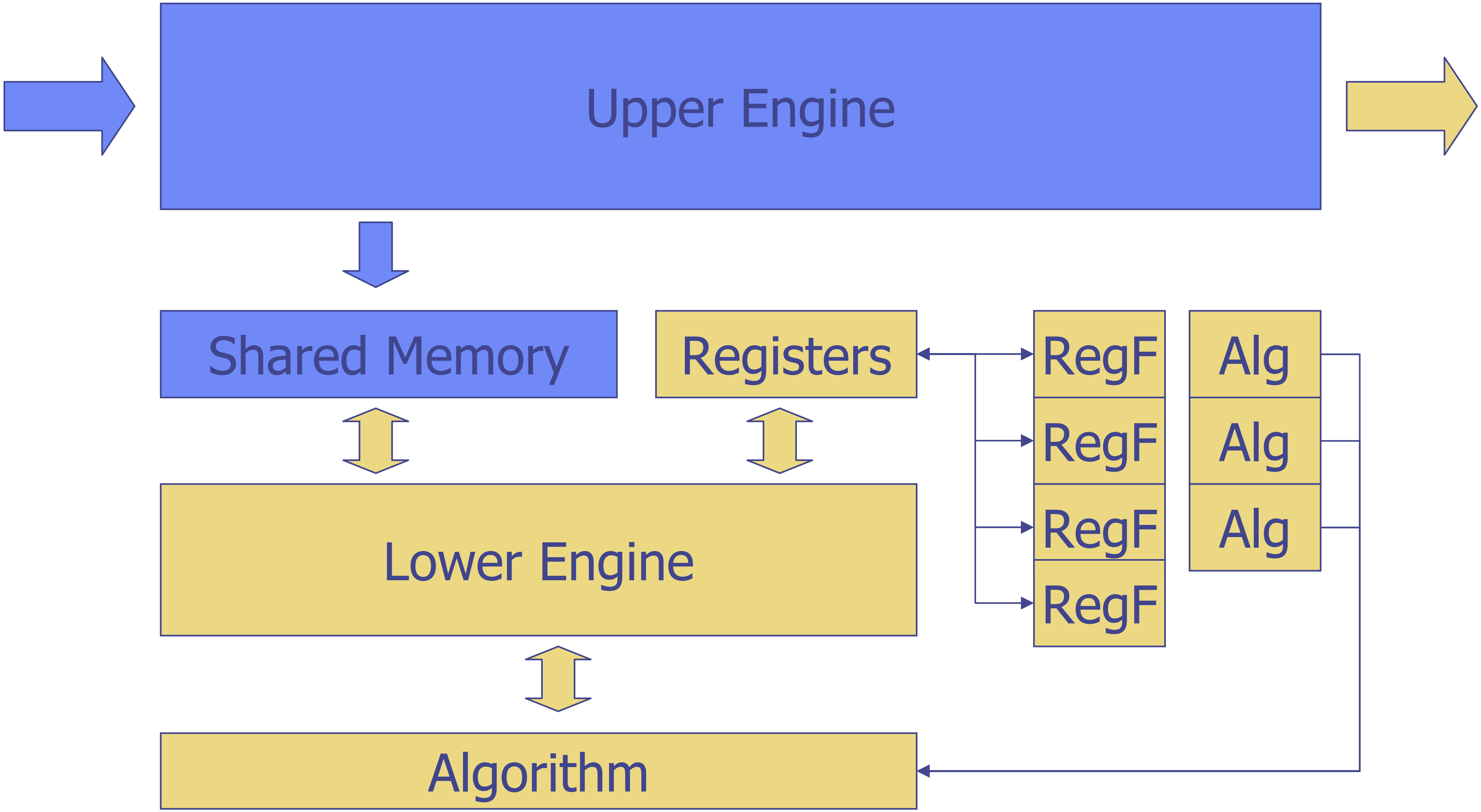
- Our goal is to build tools that will help to establish and automate validation of properties like this
- We have described the non-interference property at a high-level
- But we want to model the `chip` at a level that is closer to its implementation on silicon

Basic architecture:



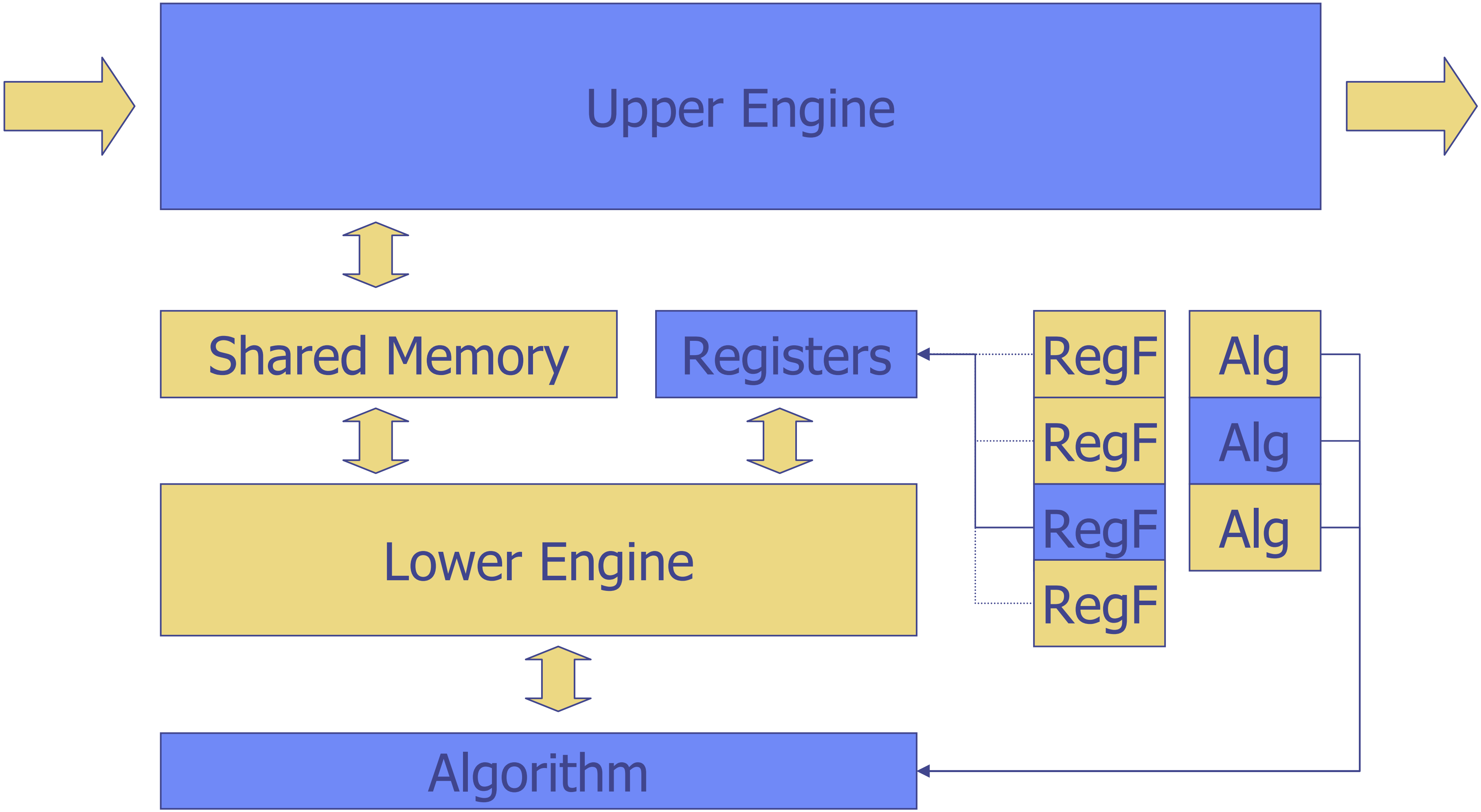
Basic architecture:

Receive packets, save in shared memory.



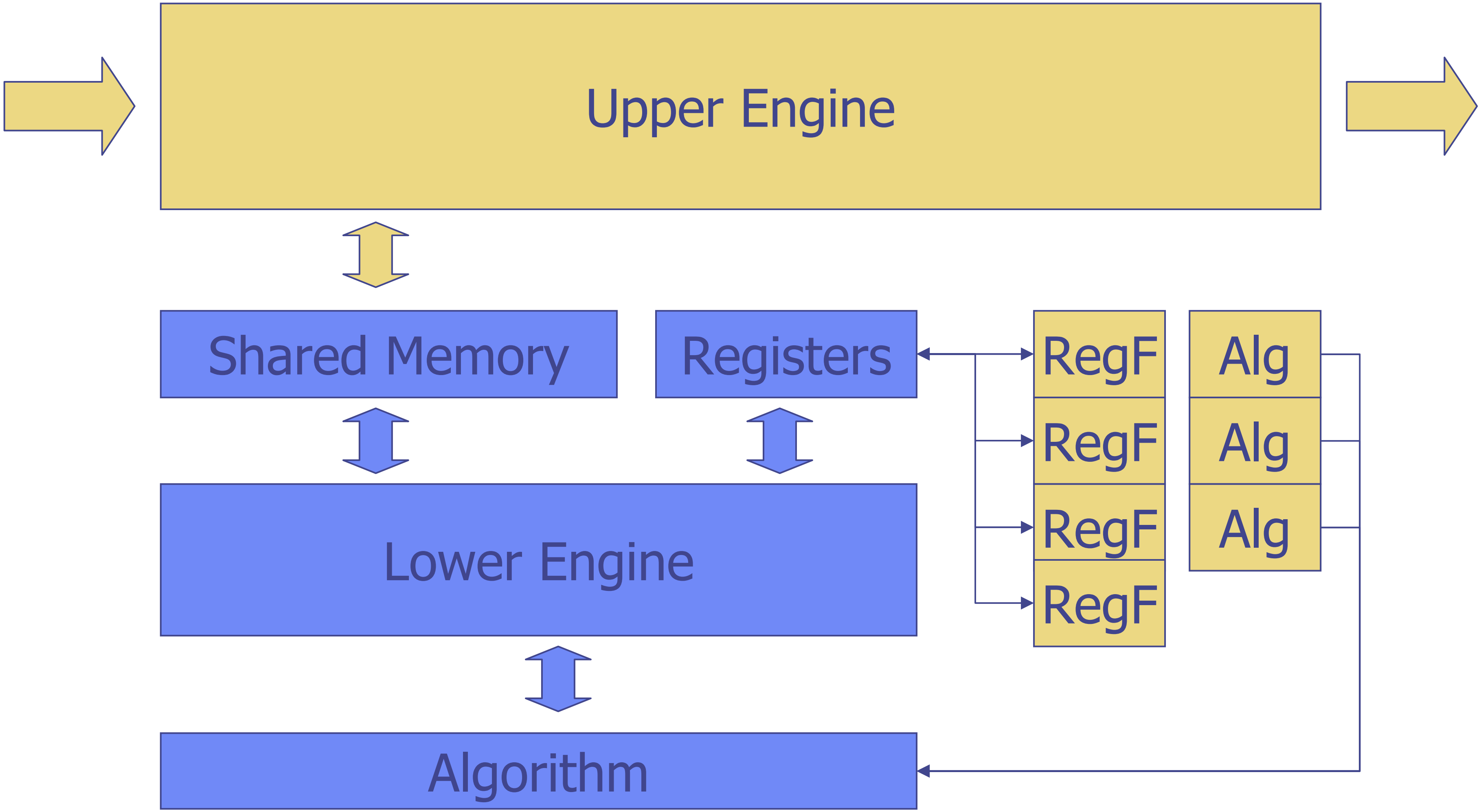
Basic architecture:

Load saved registers & algorithm for channel.



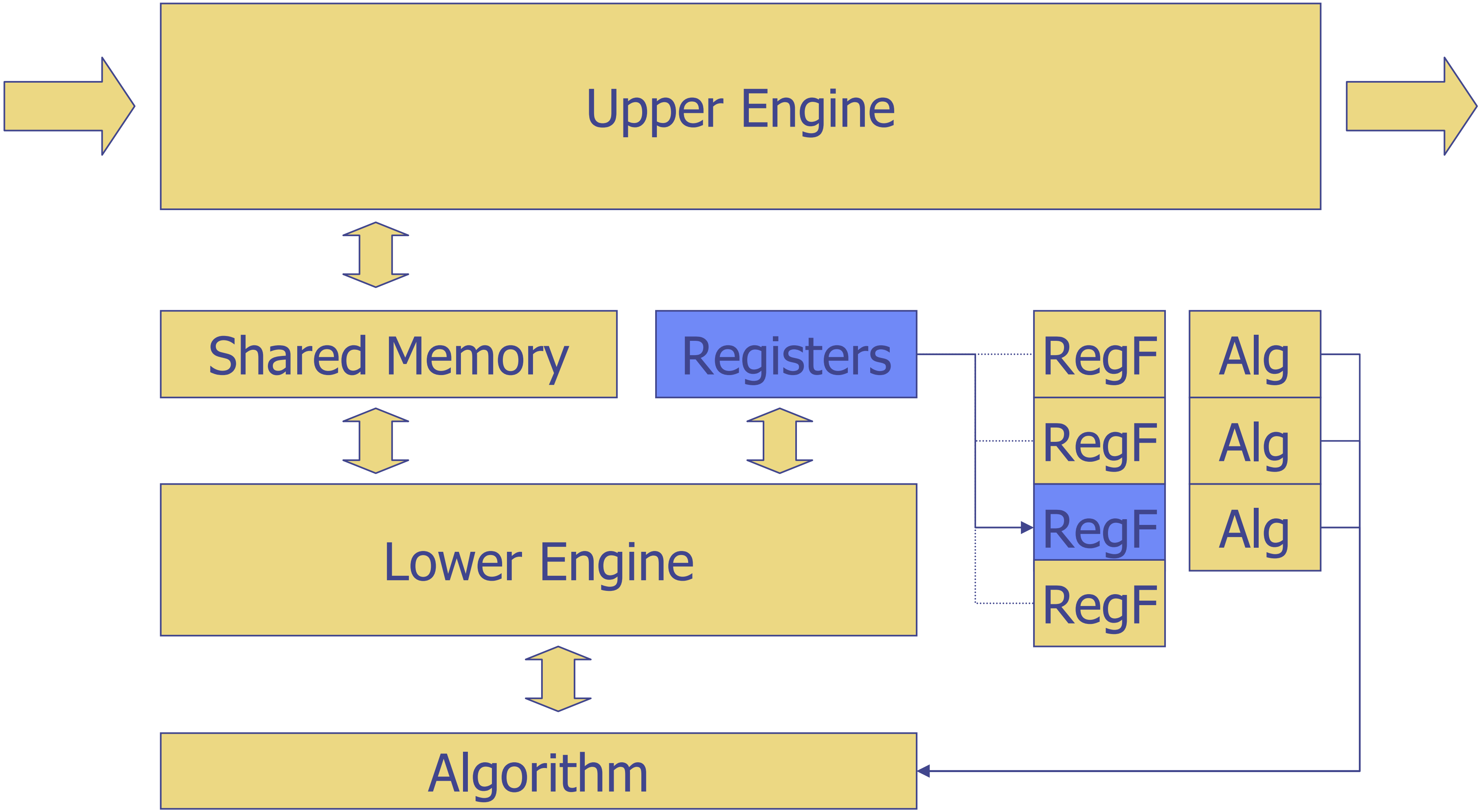
Basic architecture:

Invoke lower engine to process packet.



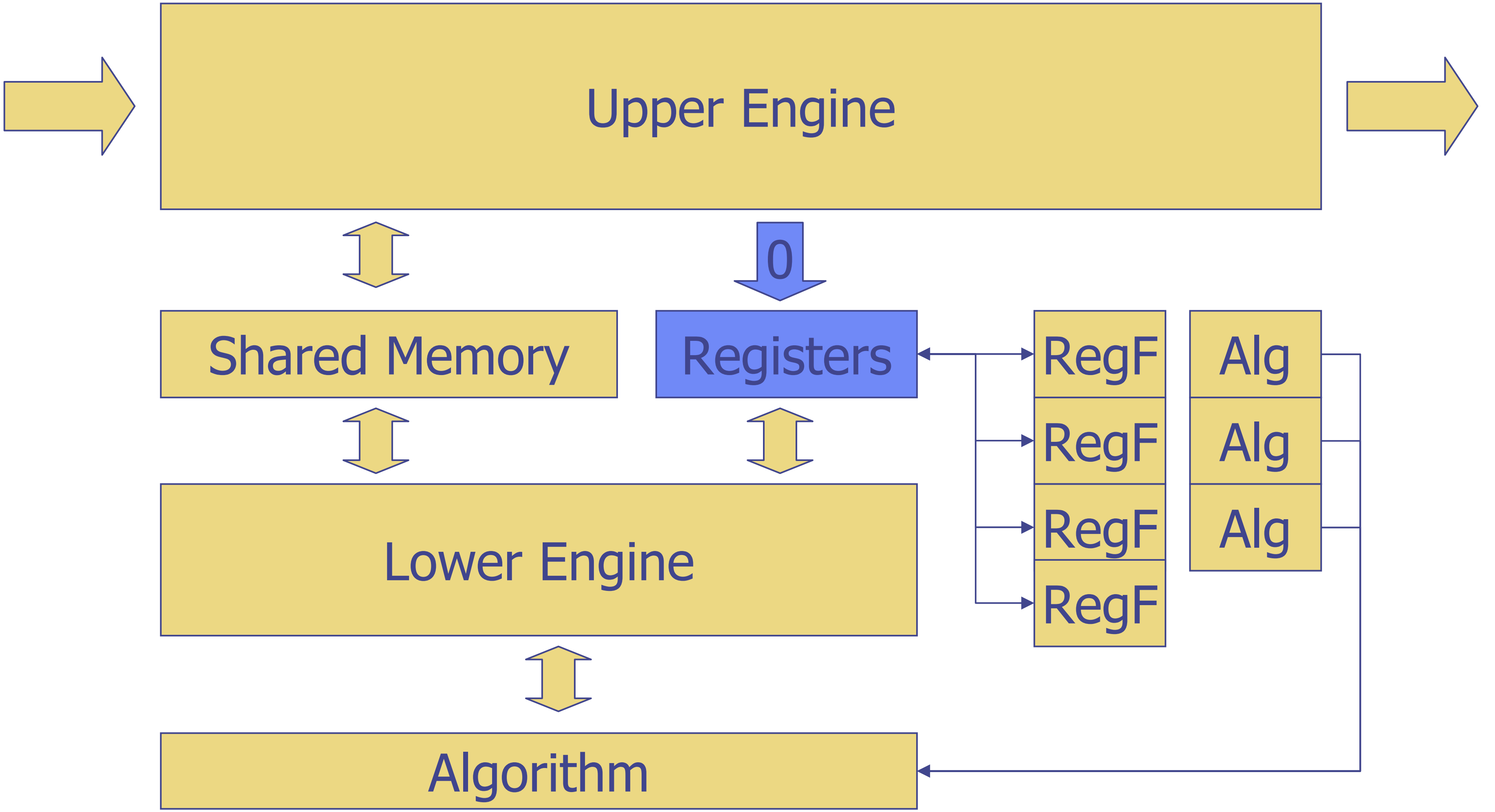
Basic architecture:

Save register set, if lower engine completes successfully.



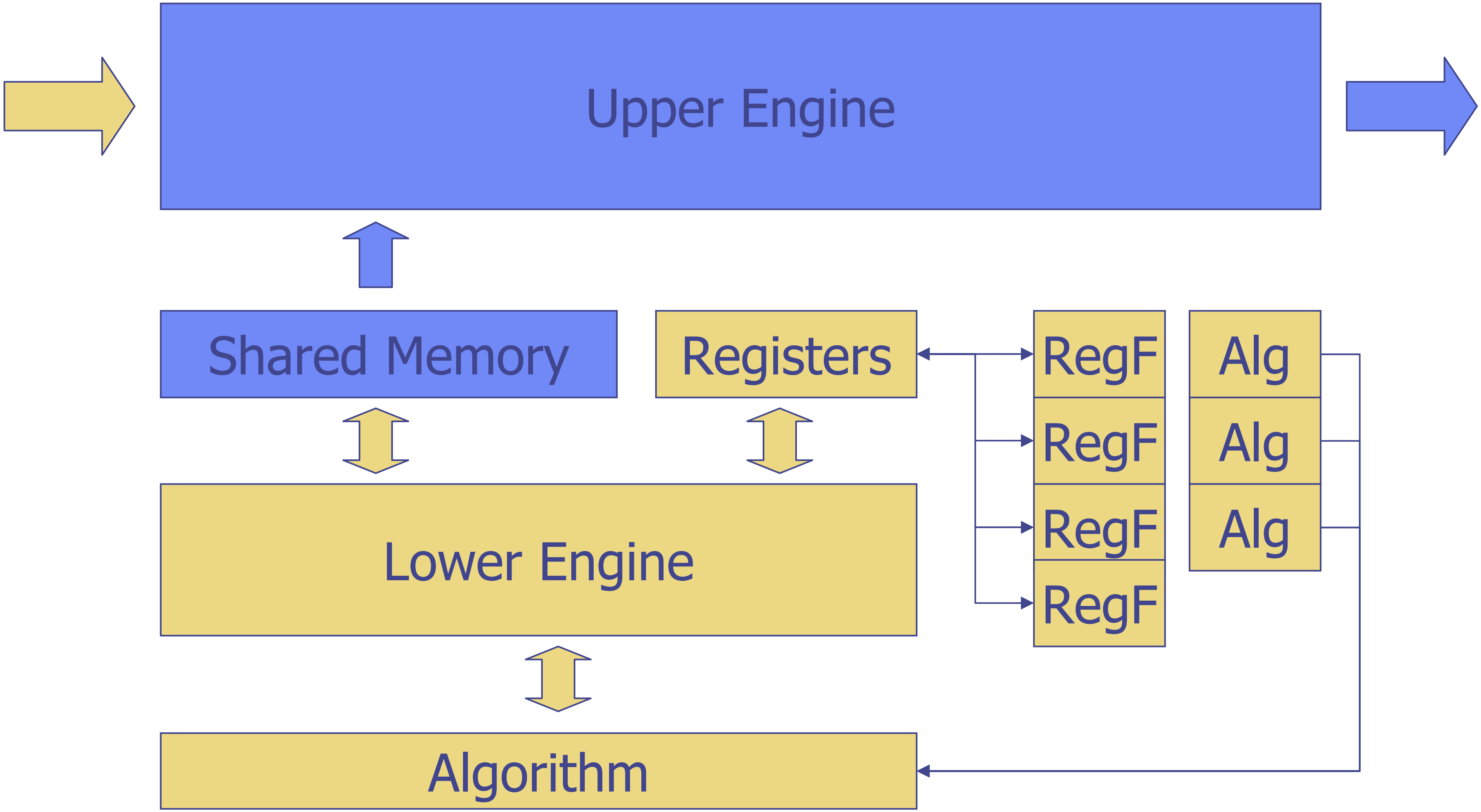
Basic architecture:

Zero out shared register set.

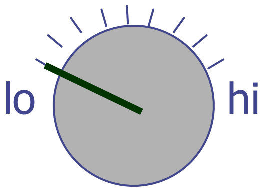


Basic architecture:

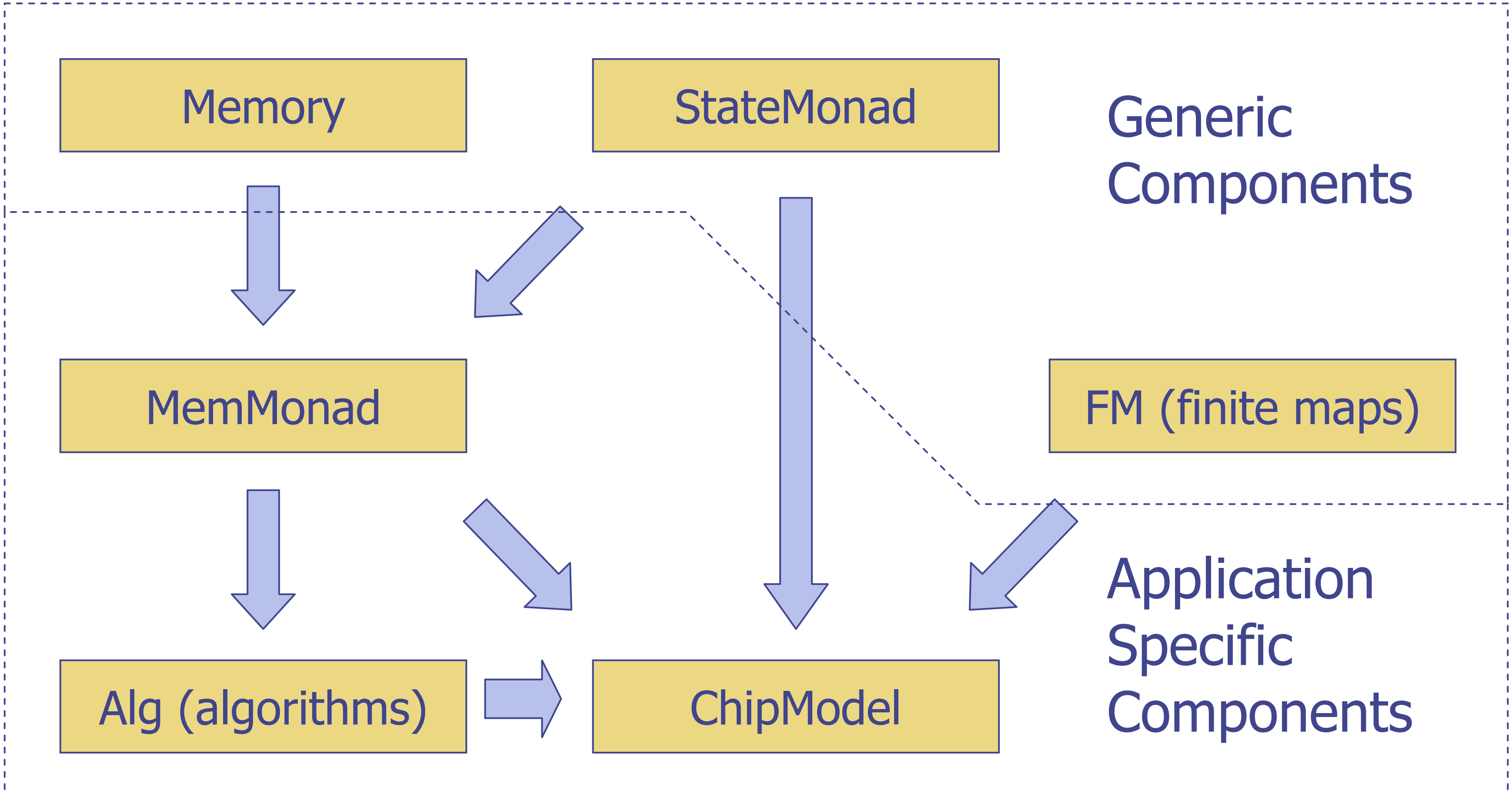
Pass processed packet data to output.



Building the Model:



We developed an executable model of the `chip` as a Haskell program: (260 LOC)



Execution (upper engine):

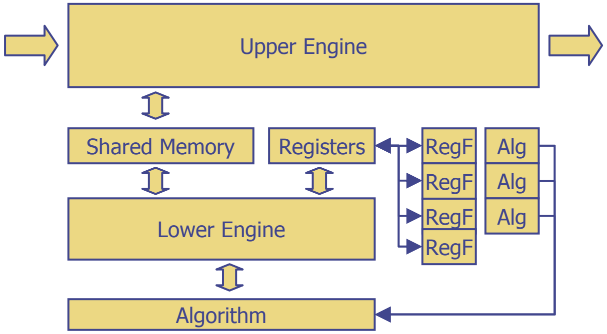
- Processing of a single packet in the upper engine is described by a function:

```
onePacket ::
       Algs ->
        Packet -> State (Memory, Regs)
                          (Maybe Packet)
```

- Processing of packet streams:

```
chip      :: Algs -> [Packet] -> [Packet]
chip algs = catMaybes .
            loop (onePacket algs)
                 (initMem, initRegs)
```

Execution (upper engine):




```
onePacket algs (chan, ws)
 = do regs  <- inSnd readState
      rng   <- inFst (malloc ws)
      let alg      = algs `at` chan
          regfile = regs `at` chan
          valid   = includes rng
          code    = runAlg (alg (fst rng) regfile)
      res   <- inFst (runProtected valid code)
      case res of
        Nothing         -> return Nothing
        Just regfile' ->
         let regs' = extend chan regfile' regs
         in do inSnd (setState regs')
               packet <- inFst (readPacket rng)
               return (Just (chan, packet))
```

Why Haskell?

One reason: no hidden side-effects

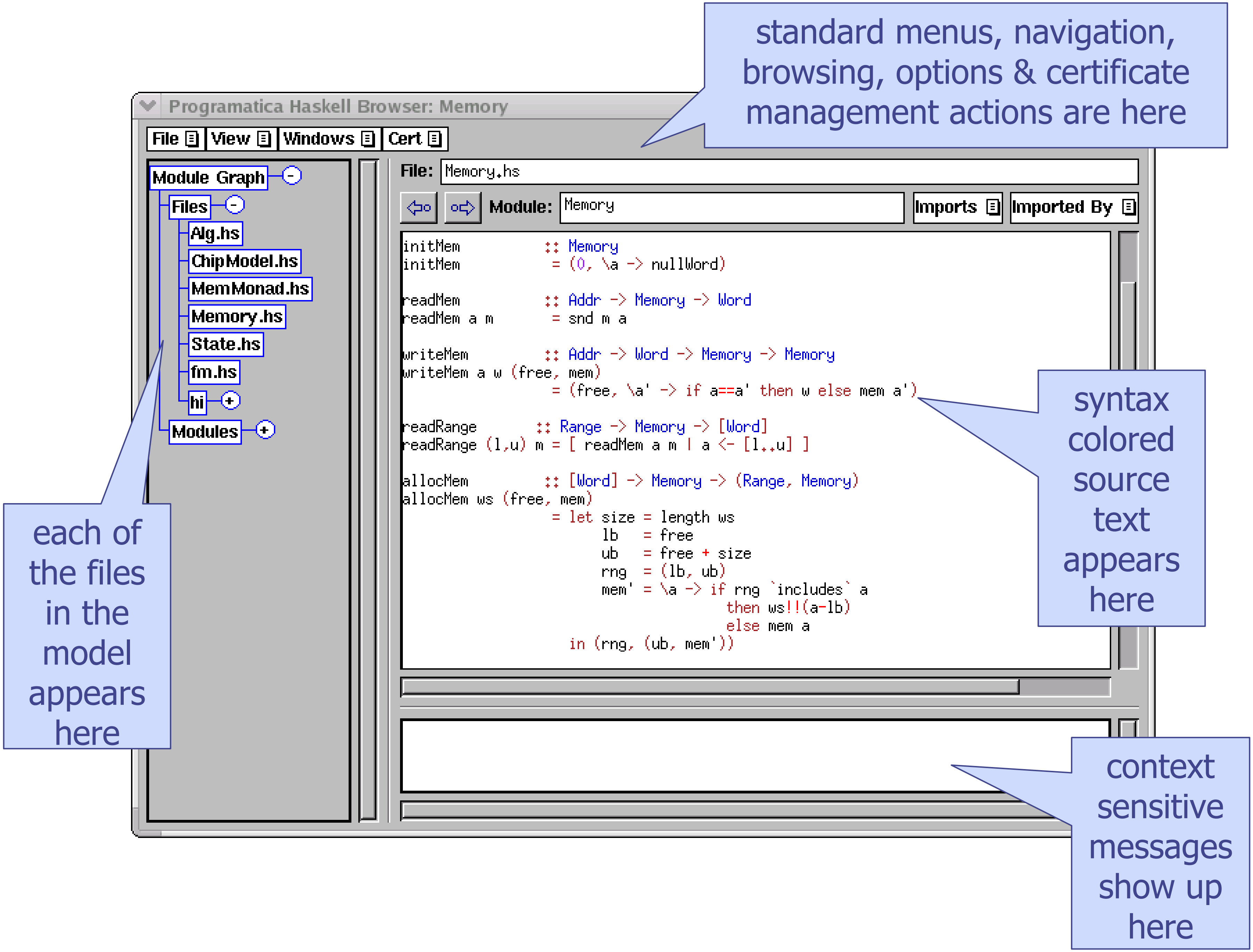
- **Purity**: if `f` is a function of type $A \to B$, the result of `f x` will depend only on `x`

- **Monads**: using abstract datatypes to encapsulate and control the scope of effects explicitly:

```
inFst (runProtected valid code)
```

  Language semantics enforces protection, without lower level OS/API wrapper.

See Peter White's talk for more …


standard menus, navigation, browsing, options & certificate management actions are here
Programatica Haskell Browser: Memory
File
View
Windows
Cert
Module Graph
Files
Alg.hs
ChipModel.hs
MemMonad.hs
Memory.hs
State.hs
fm.hs
hi
Modules
File: Memory.hs
Module: Memory
Imports
Imported By
initMem :: Memory
initMem = (0, \a -> nullWord)
readMem :: Addr -> Memory -> Word
readMem a m = snd m a
writeMem :: Addr -> Word -> Memory -> Memory
writeMem a w (free, mem)
= (free, \a' -> if a==a' then w else mem a')
readRange :: Range -> Memory -> [Word]
readRange (l,u) m = [readMem a m | a <- [l..u]]
allocMem :: [Word] -> Memory -> (Range, Memory)
allocMem ws (free, mem)
= let size = length ws
lb = free
ub = free + size
rng = (lb, ub)
mem' = \a -> if rng `includes` a
then ws!!(a-lb)
else mem a
in (rng, (ub, mem'))
syntax colored source text appears here
each of the files in the model appears here
context sensitive messages show up here

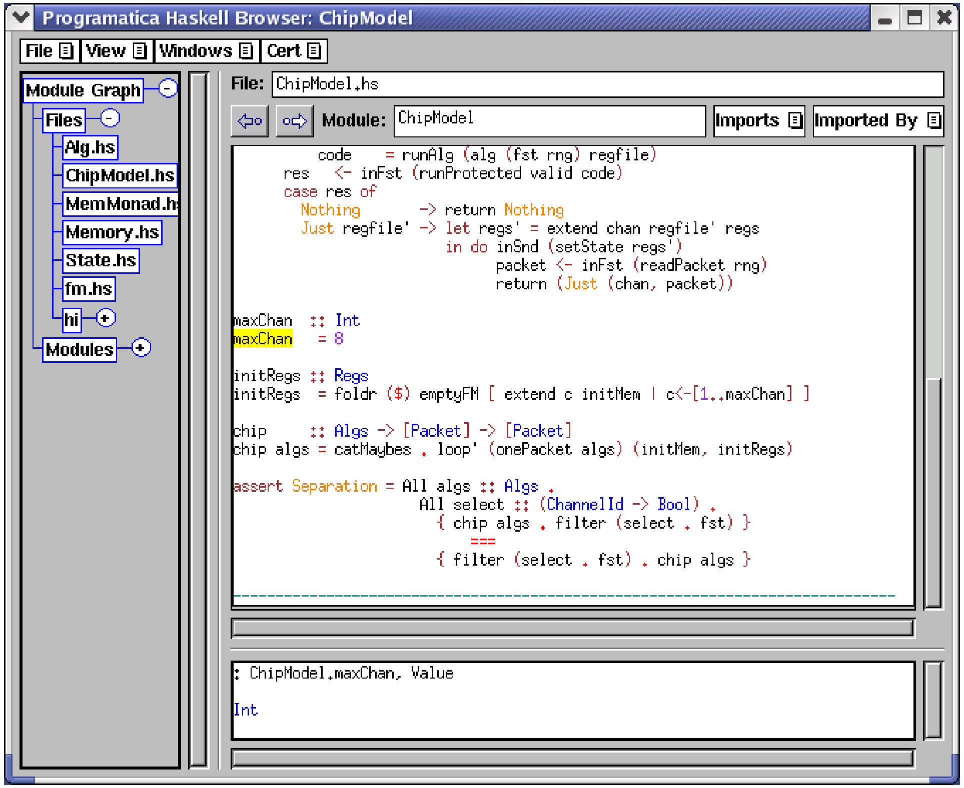
The Programatica Front End:

- The GUI, `pfebrowser`, usually provides the most convenient interface for working with Programatica
- A command line tool, `pfe`, is also available
- Both are useful tools in their own right for Haskell programmers

```
Usage: pfe [options] <command>
  where <command> is one of:
    new <files> -- create a new project containing <files>
    add <files> -- add files to the project
    remove <files> -- remove files from the project
    files -- list files in the project
    options -- show options in effect
    modules <modules> -- list modules in the project
    graph <modules> -- show module dependecy (sub)graph
    dotgraph <modules> -- dot format module dependency graph
    revgraph <modules> -- show reverse module dependecy (sub)graph
    unused <modules> -- show unimported and unreachable modules
    prune <modules> -- remove unreachable modules from the project
    file <modules> -- which file is the module in
    module <files> -- which module does the file contain
    defined <modules> -- list entities defined in the module
    free <modules> -- list names referenced but not defined in the module
    pragmas <modules> -- extract pragmas from modules
    lex <files> -- show the result of lexical analysis
    exports <modules> -- list entities exported by the modules
    find <identifiers> -- find exported entities with the given names
    inscope <modules> -- list entities in modules' top-level environment
    pp <modules> -- parse and pretty-print modules
    tc <modules> -- type check and display decorated modules
    tcpb <modules> -- remove pattern bindings, then tc
    tclc <modules> -- remove list comprehensions, then tc
    types <modules> -- show types/kinds of top-level entities
    instances <modules> -- list instances defined in a module
    iface <modules> -- show the interfaces of modules
    usedtypes <modules> -- show what types identifers are used at
    chase <files> -- look for imported modules in given files/directories
    htmlfiles <modules> -- generate HTML files for modules
    deps <modules> -- compute dependency graph for value definitions
    tdeps <modules> -- compute dependency graph for value definitions
    dotdeps <modules> -- dot format dependency graph for value definitions
    tdotdeps <modules> -- dot format dependency graph for value definitions
    needed <M1.x1 ... Mn.xn> -- needed values
    tneeded <M1.x1 ... Mn.xn> -- needed values
    neededmodules <M1.x1 ... Mn.xn> -- names of modules containing needed values
    tneededmodules <M1.x1 ... Mn.xn> -- names of modules containing needed values
    dead <M1.x1 ... Mn.xn> -- dead code (default: Main.main)
    tdead <M1.x1 ... Mn.xn> -- dead code (default: Main.main)
    uses <M.x> -- find uses of an entity
    assertions <modules> -- list names of named assertion
    asig <M.x> -- write an assertion signature to stdout
    tasig <M.x> -- write an assertion signature to stdout
    adiff <M.x> -- compare an assertion signature with stdin
    tadiff <M.x> -- compare an assertion signature with stdin
    qc <modules> -- translate to QuickCheck
    slice <M.x> -- extract a slice (needed part) of the program
    pqc <M.x> -- pruned translation to QuickCheck
    qcslice <M.x> -- translate a slice to QuickCheck
    prove <modules> -- translate to Stratego
    clean -- list files in the project
```

A Development Environment:

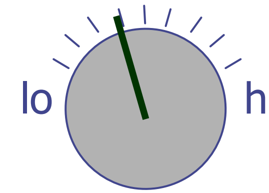
- Standard Haskell compilers and interpreters are used to compile and execute code



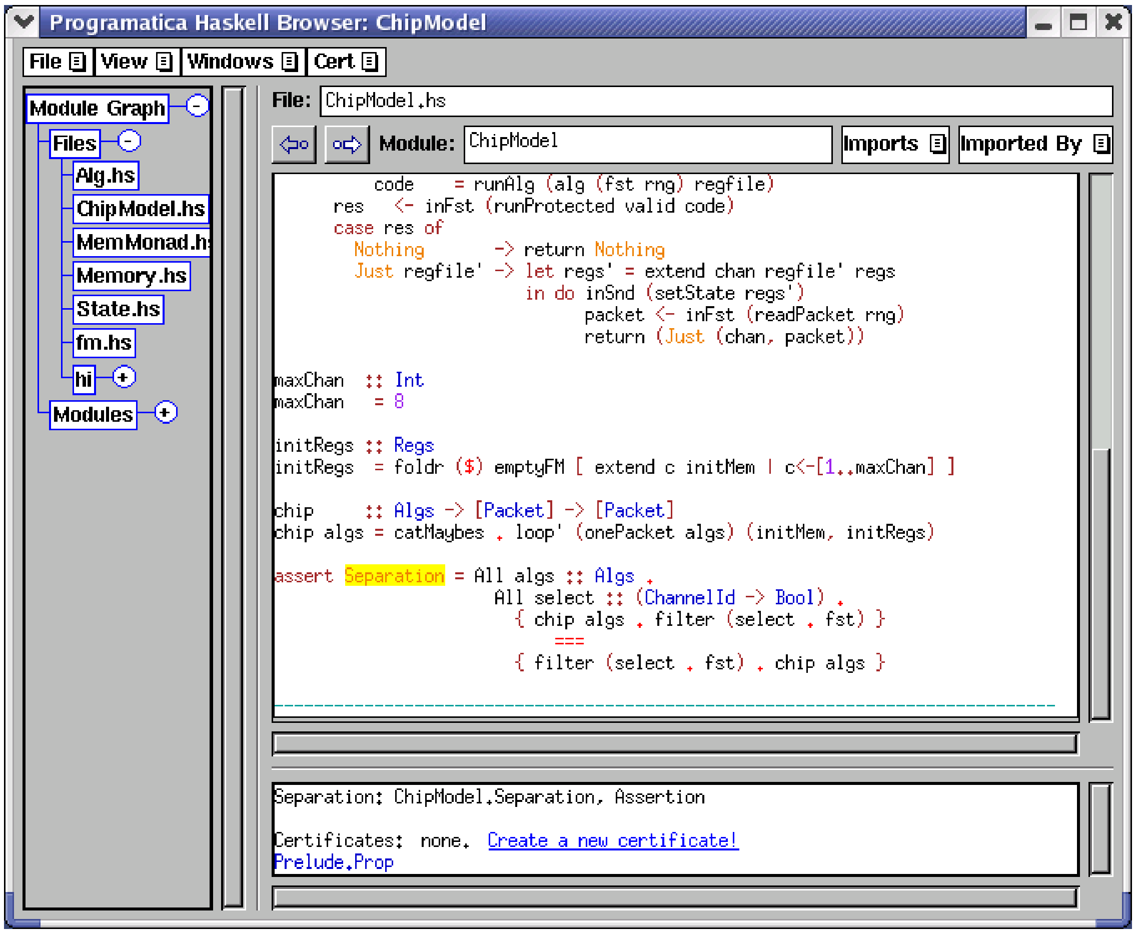
- pfebrowser provides sophisticated browsing capabilities with hyperlinking, integrated type checking, …

- Programatica is a program development environment

Using Properties:



We annotated the model with properties …



… and quickly spotted bugs in our code!

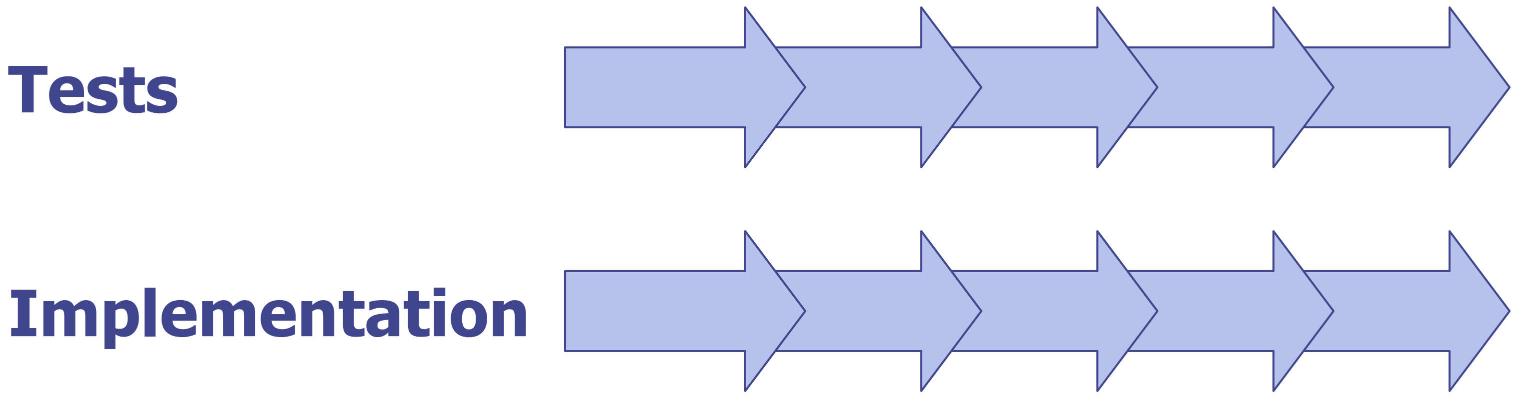
Programatica: "Programming as if Properties Matter"

Properties are
- written
- parsed
- analyzed
- type-checked

as an integral part of the source text

Goals:
- Maintain consistency between code and properties
- Capture programmer expectations/intentions as part of the programming process
- Just writing down properties heightens thinking about correctness

Extreme Programming

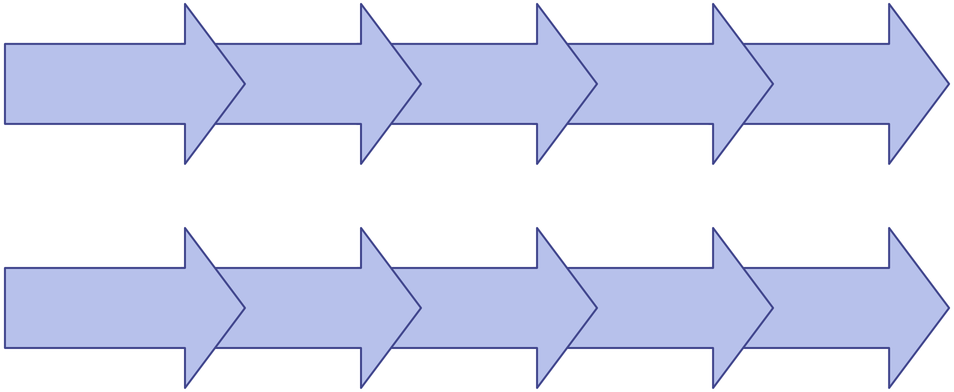


- Testing and Programming proceed hand in hand
- Testing reveals errors in the program
- Programming reveals errors in the test cases

“Extreme Formal Methods”

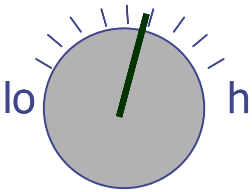
Specification

Implementation

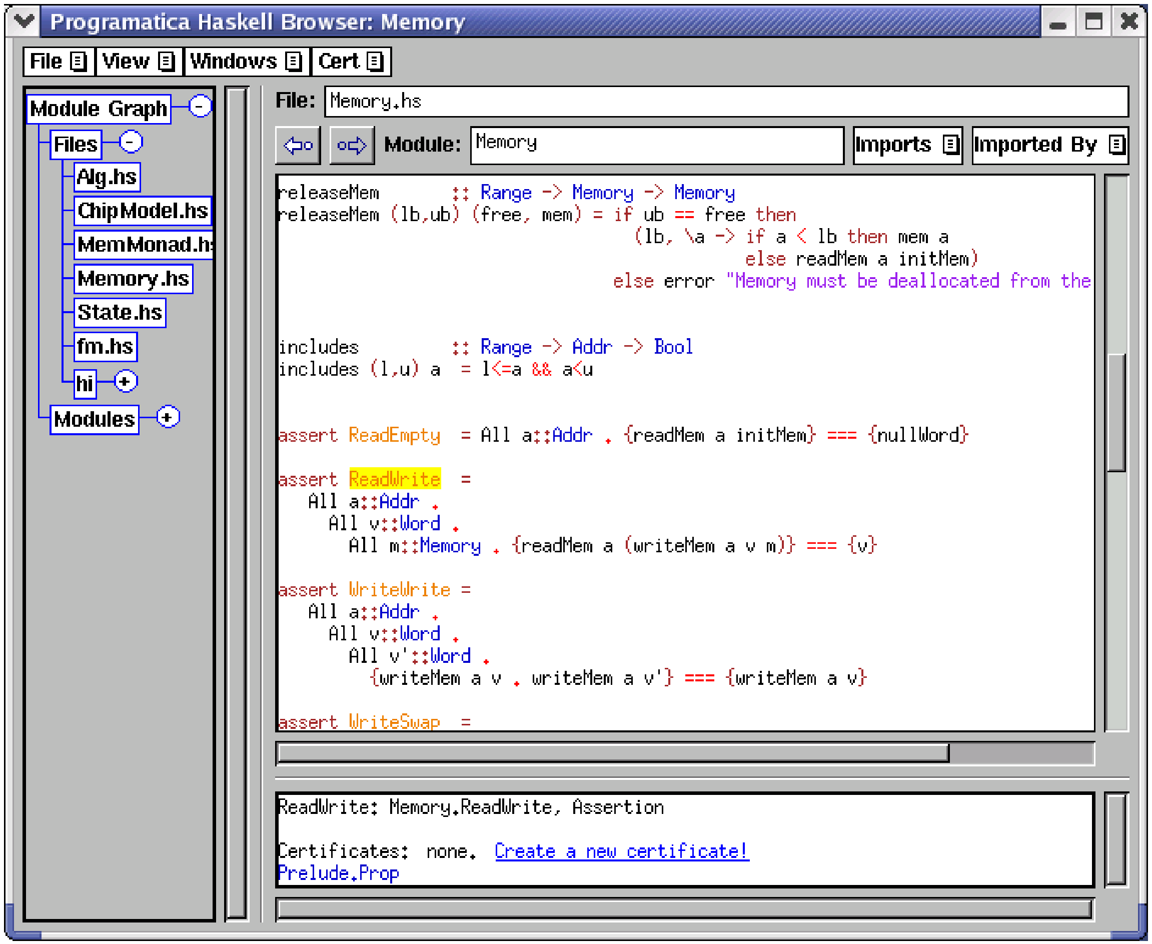


- Programming and Validation proceed hand in hand
- Validation reveals errors in the program
- Programming reveals errors in the specification

Generating Evidence:

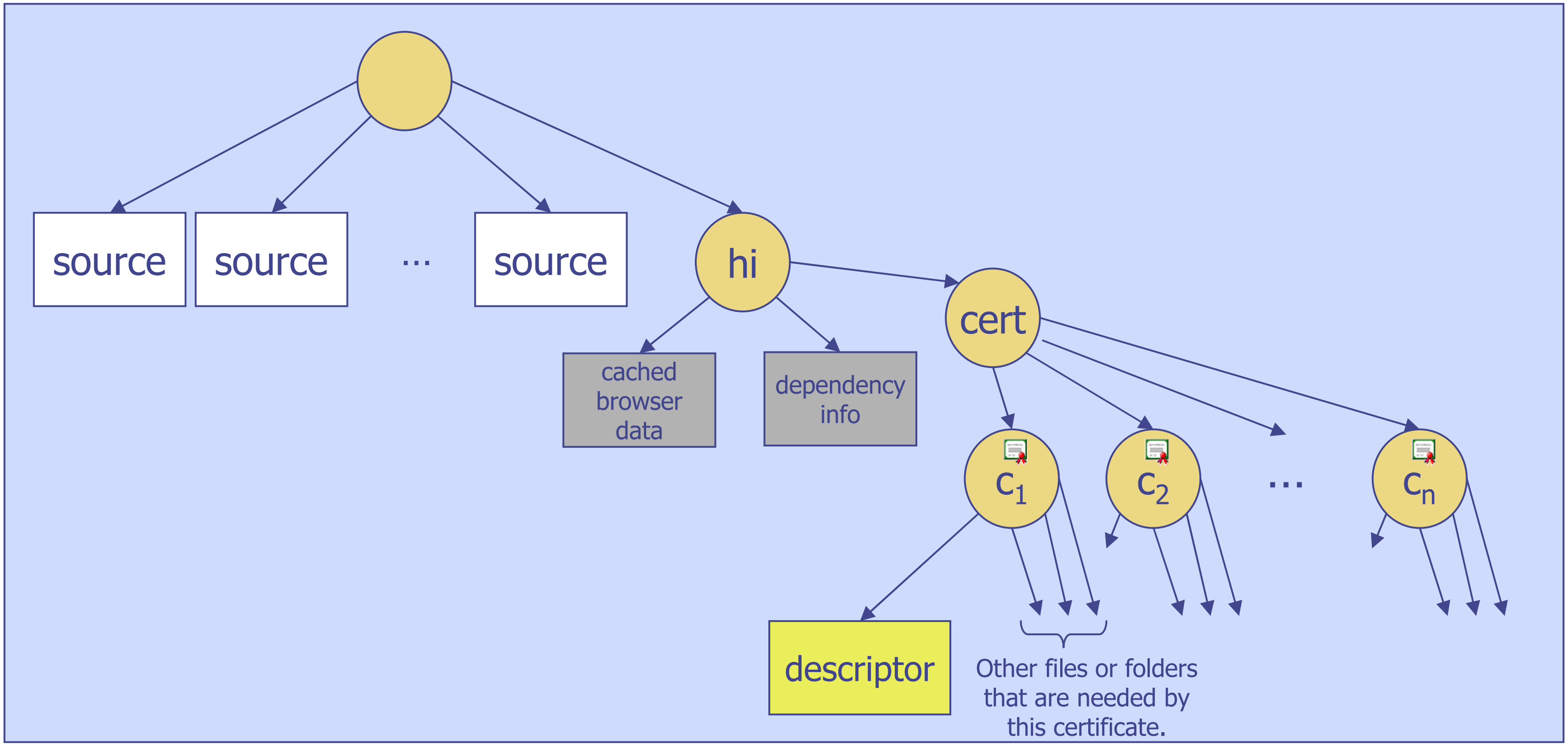


We began the process of validation, using QuickCheck to generate random test cases for asserted properties



... and found bugs in our **specification**!
... and bugs in our **code**!

Gathering Evidence:



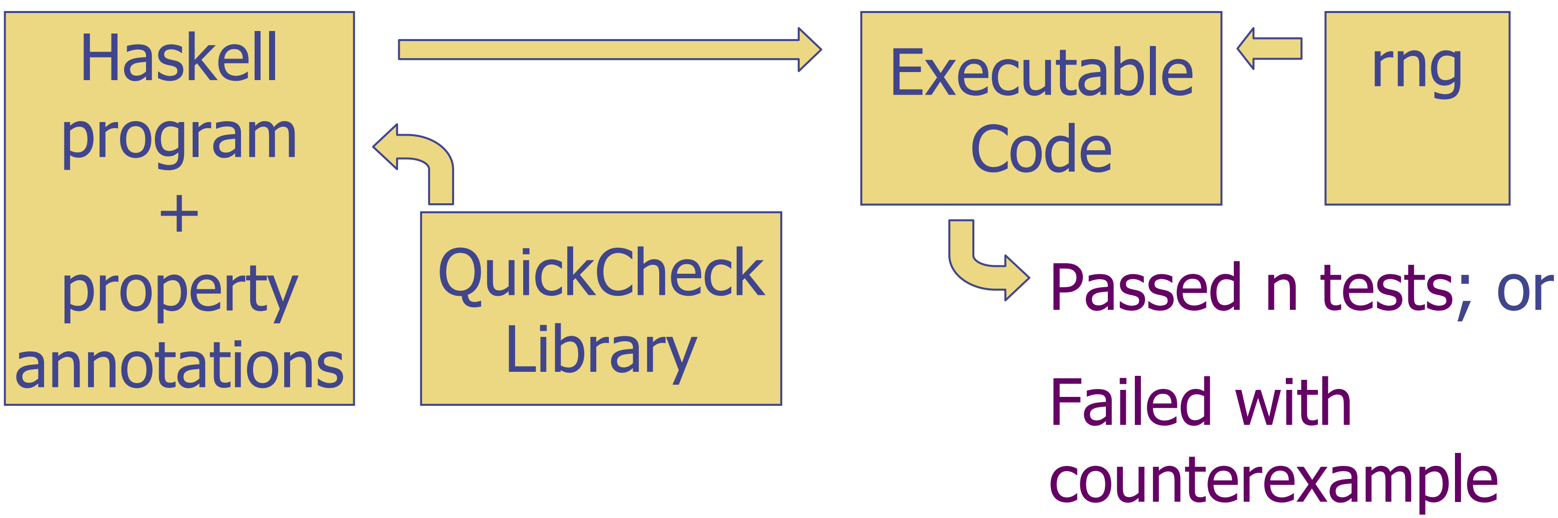
Source materials are stored with related evidence and dependency information.

A "**h**idden **i**nformation" directory is shared between the files in a package.

Using QuickCheck:

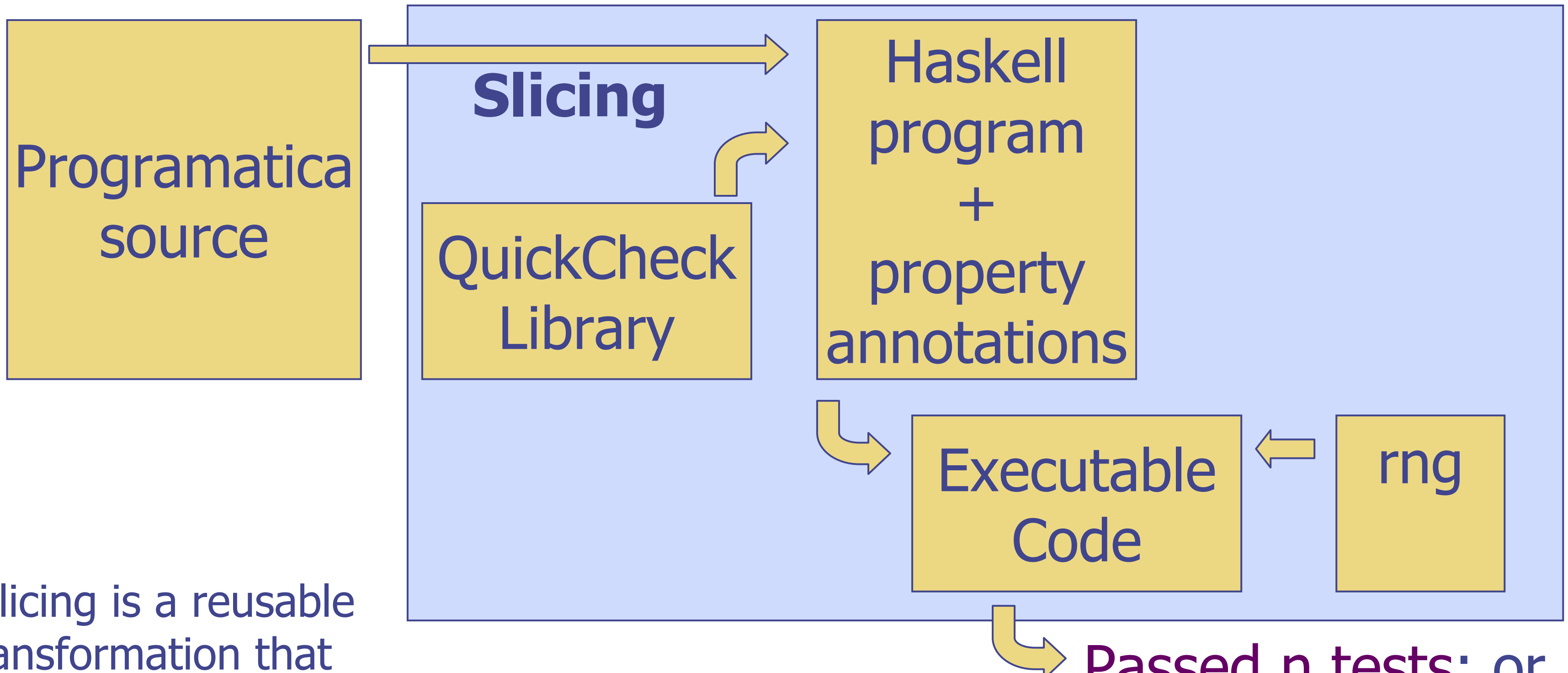
- QuickCheck is an independently developed random testing tool (Hughes and Claessen, Chalmers University, Sweden)

- Haskell developer's perspective:



Using QuickCheck with pfe:

- Programatica implementer's perspective:



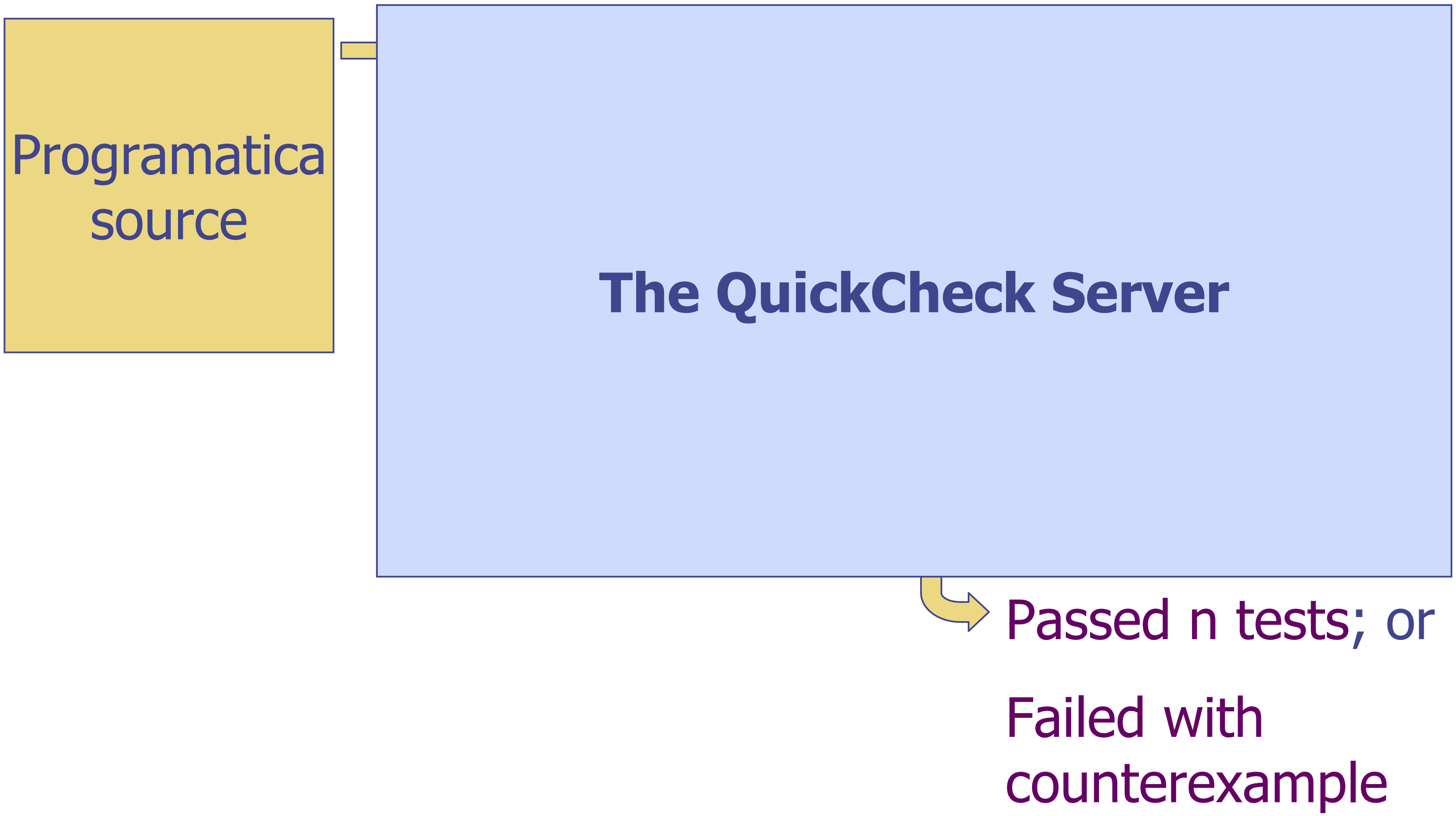
Passed n tests; or

Failed with counterexample

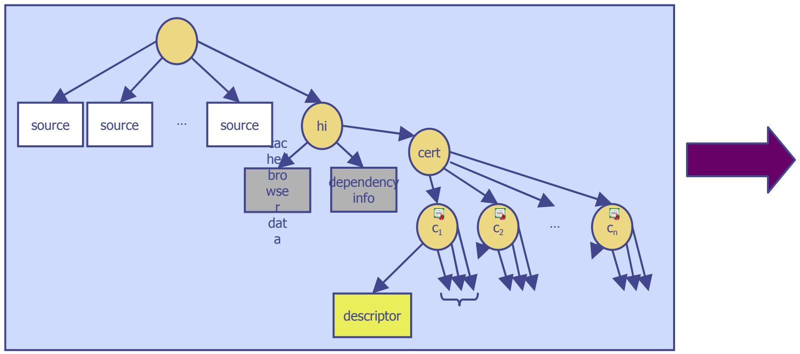
(Slicing is a reusable transformation that reduces the size of the code that is passed to QuickCheck, and eliminates spurious dependencies)

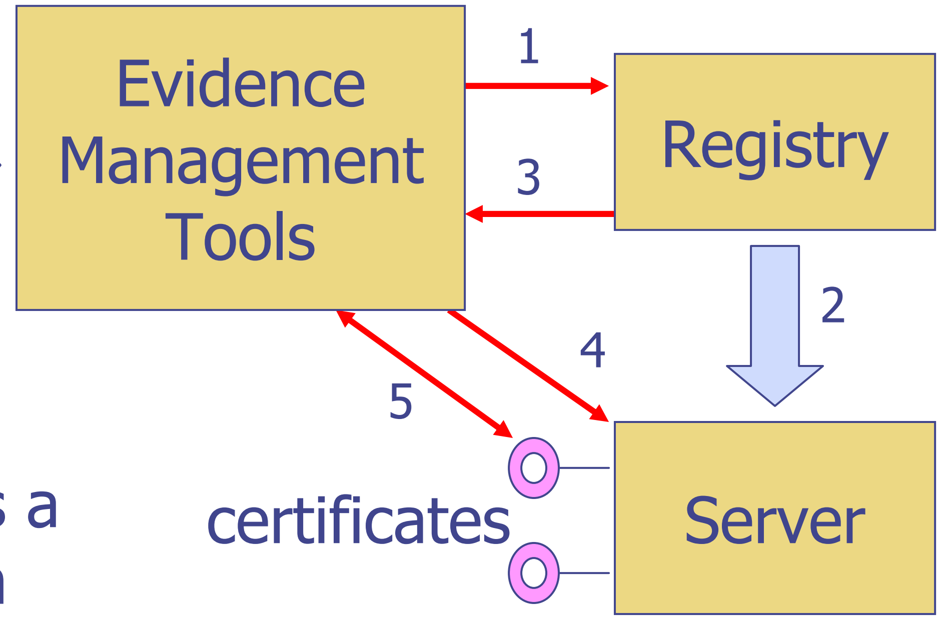
Using QuickCheck with pfe:

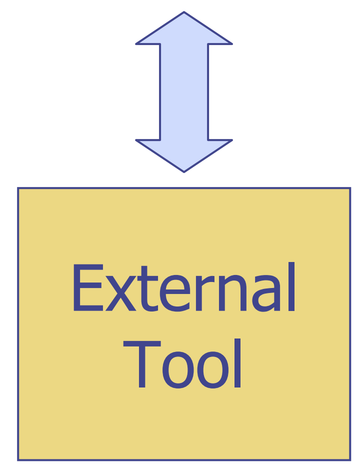
- Programatica user's perspective:



Servers and Certificates:



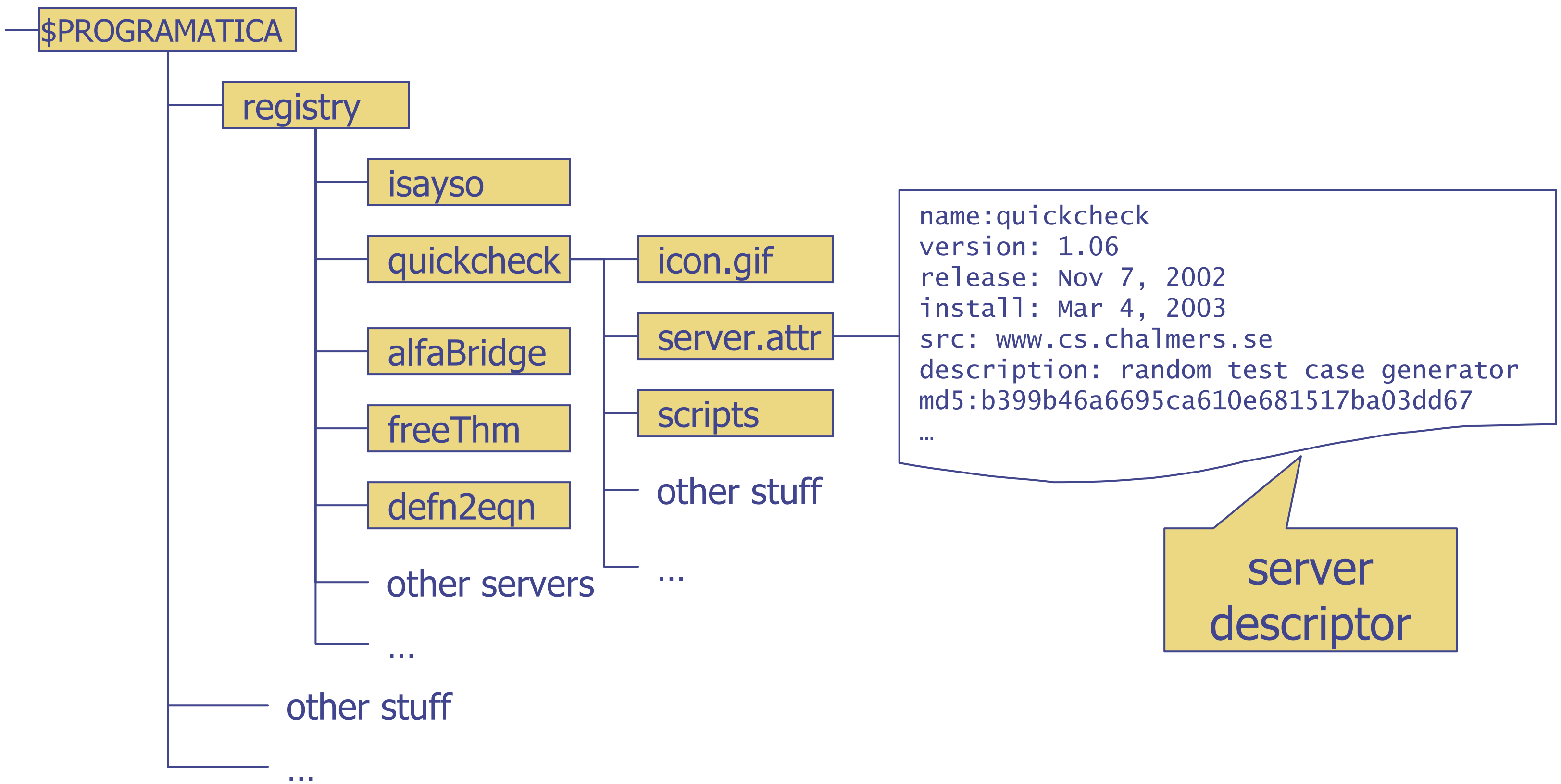




- Use of a **registry** enables a flexible, extensible system
- Use of **servers** and **certificates** permits a generic interface that automates/hides the translation between Programatica and any external tools

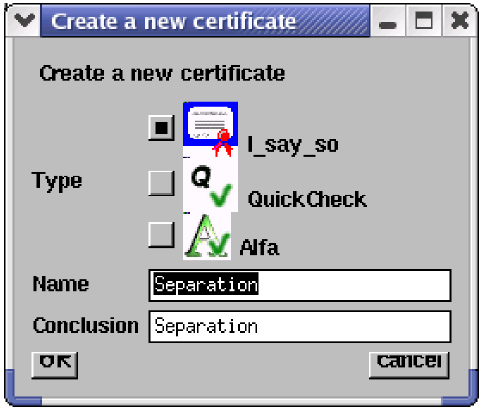
The Registry:

Once again we are exploiting the existing filesystem in a design for the registry that is extensible, language neutral, and portable:



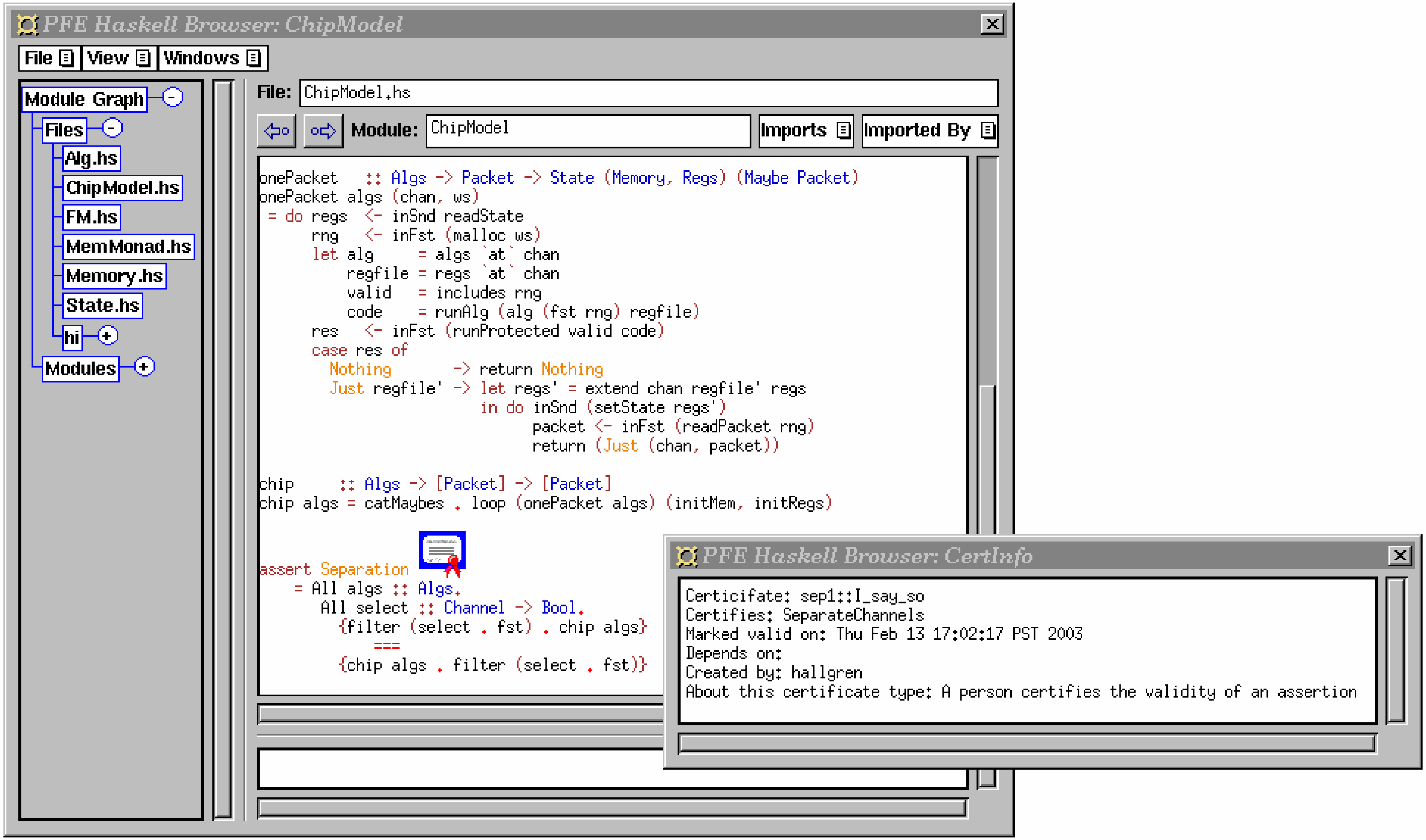
Servers in pfe:

- Current implementation includes:
  - "Paper and Pencil" (I say so!)
  - QuickCheck
  - Alfa (a proof assistant based on constructive type theory)

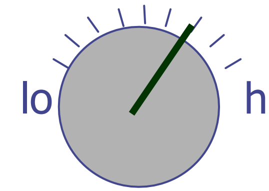


- Others currently in progress/under consideration include:
  - Free theorem generator
  - Regression testing
  - Isabelle (HOL theorem prover)
  - Bounded model checker

Certificates in pfebrowser:

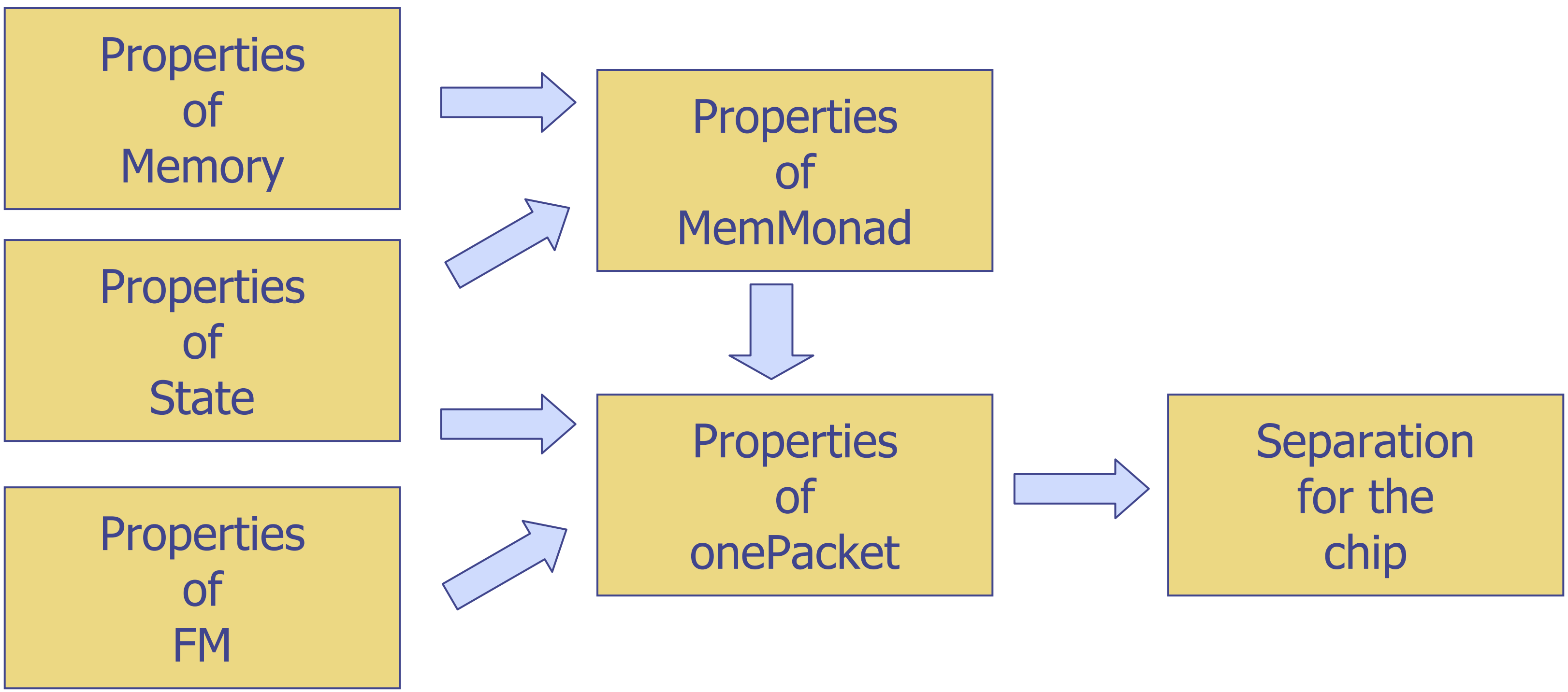


Stronger Evidence:

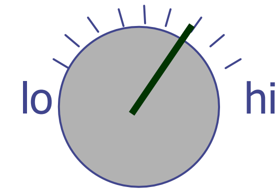


We began to construct a formal (hand) proof of Separation …

The overall structure is modular:



Combining Evidence:



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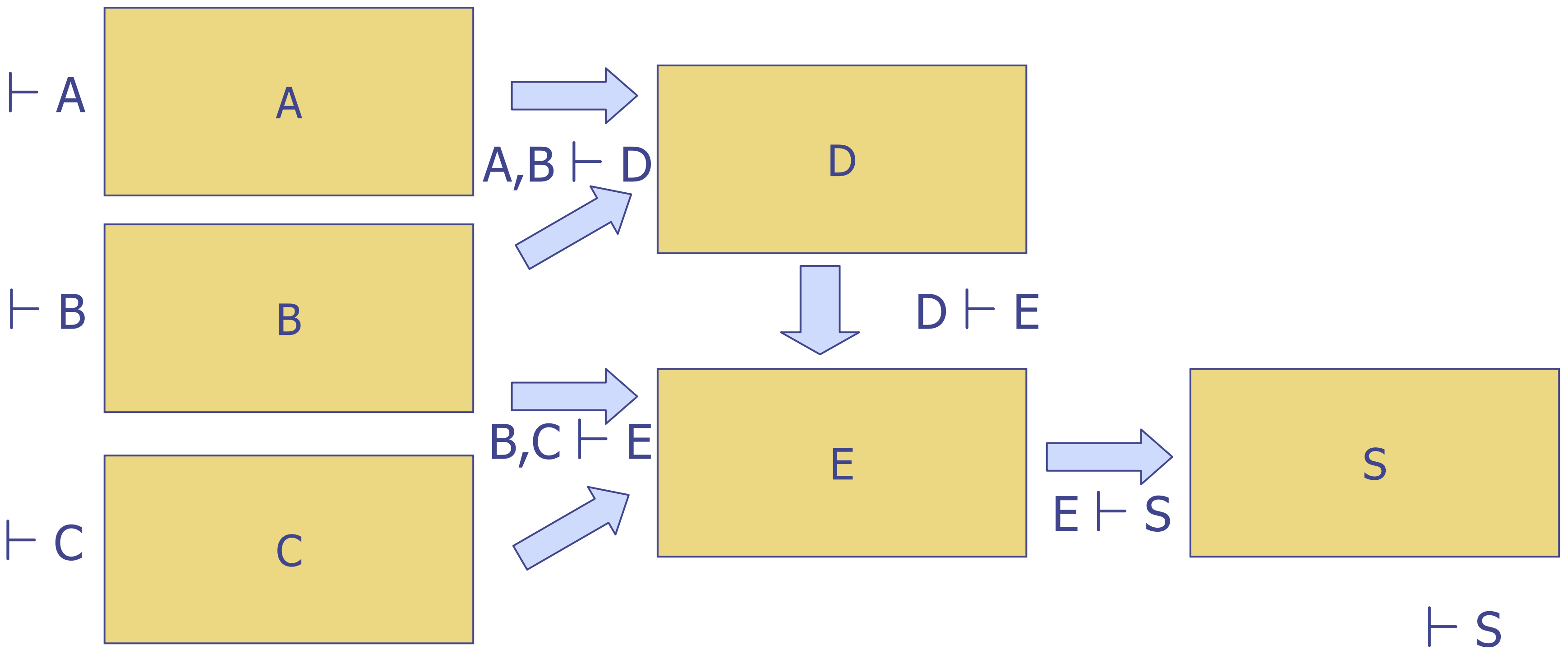
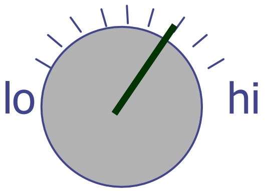


Validation and Combination:

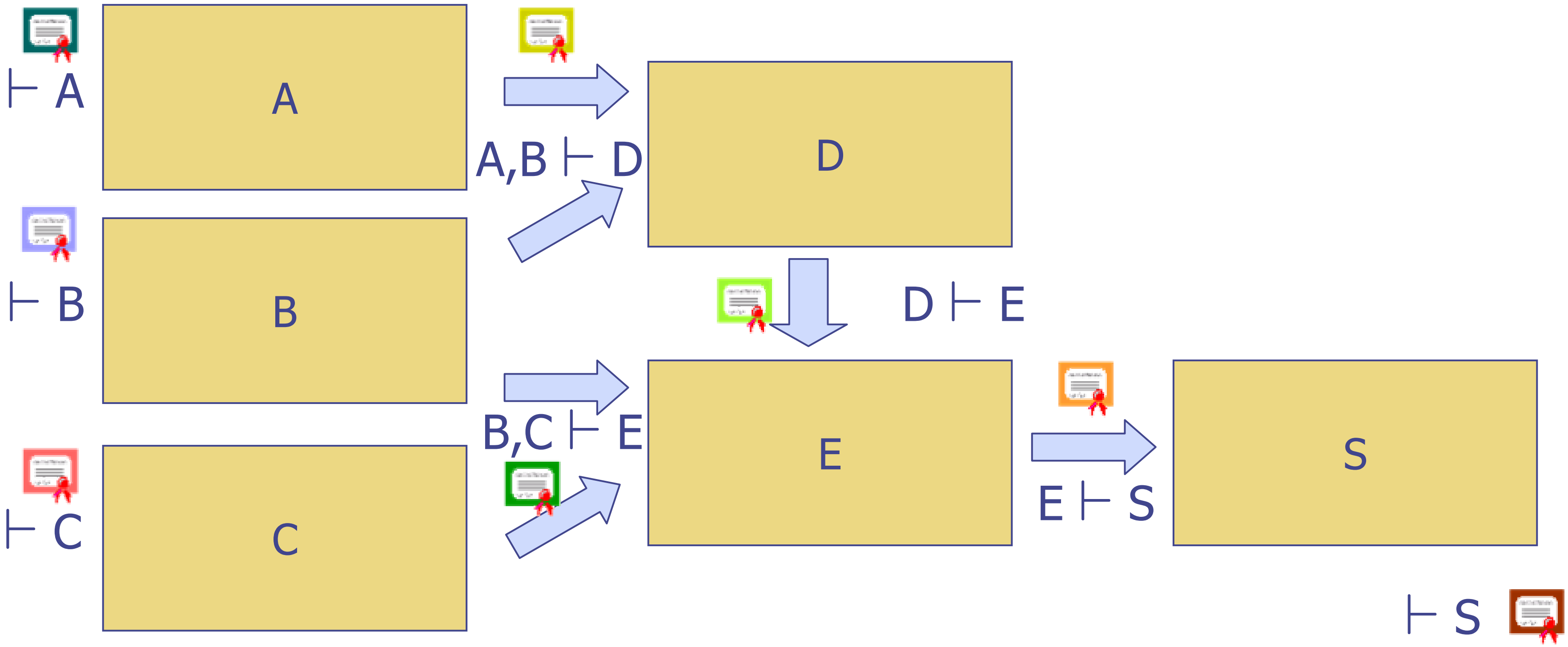
We want to validate and combine evidence from different sources:

- Certificates carry **sequents** "Assume $\vdash$ Conclude" that act as an interface/contract between Programatica and any external tools.
- Servers for external tools are used to test **validity** (i.e., to check that a certificate's sequent is consistent with its evidence)
- Built-in servers use sequents of existing certificates to guide the construction of new, composite certificates.

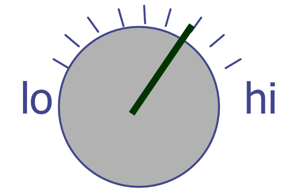
Integrating Evidence:



Multiple tools can play a role in validating or assuring behavior of the system as a whole:

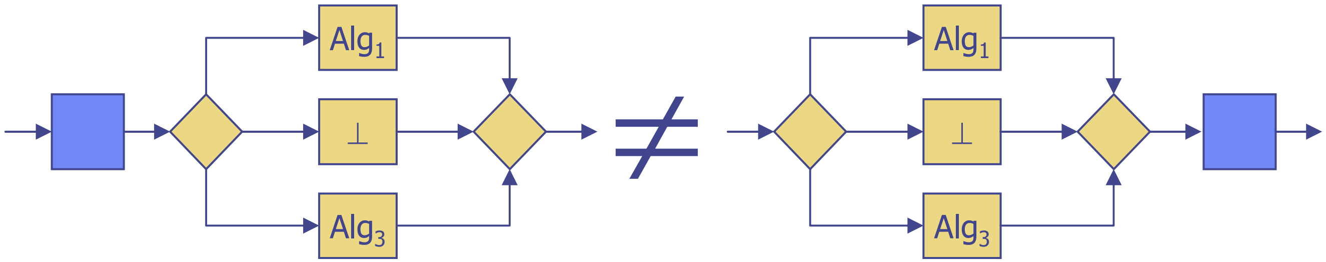


Separation Fails!:



We uncovered two bugs in our attempt to prove separation:

- Separation fails if an algorithm can fail to terminate



- Separation fails because the algorithm for a channel sees the absolute address of packets in shared memory.
  - Is this a bug in the code or the specification?
  - Is this a security loophole?
  - Several fixes are available: relative addressing, zeroing out memory, etc…

This is useful feedback for the designer/developer to discuss!

Dealing with Change:

- Our model, our specification, or both must be revised to complete the task in hand
- Whatever happens, some of the evidence we have collected may no longer be valid.
- Some evidence can be reconstructed automatically, but some will be quite expensive to reconstruct
- In software development, change is the norm, not the exception, so we need to handle change as efficiently as possible.

Hashing to Detect Change:

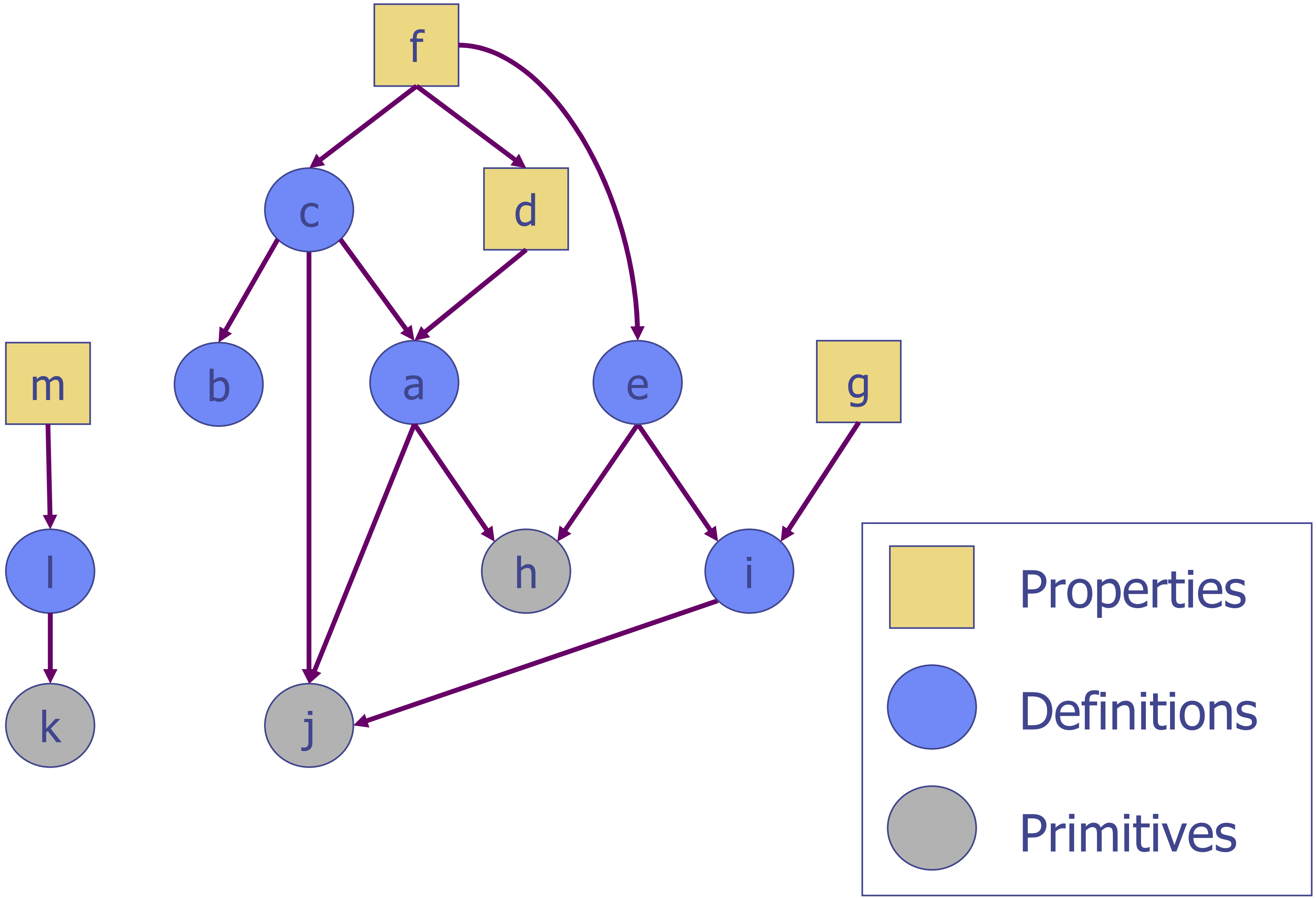
- When we parse a source file, we calculate a cryptographically robust hash (e.g., MD5) over the abstract syntax of each definition

- These hashes are cached as hidden information:

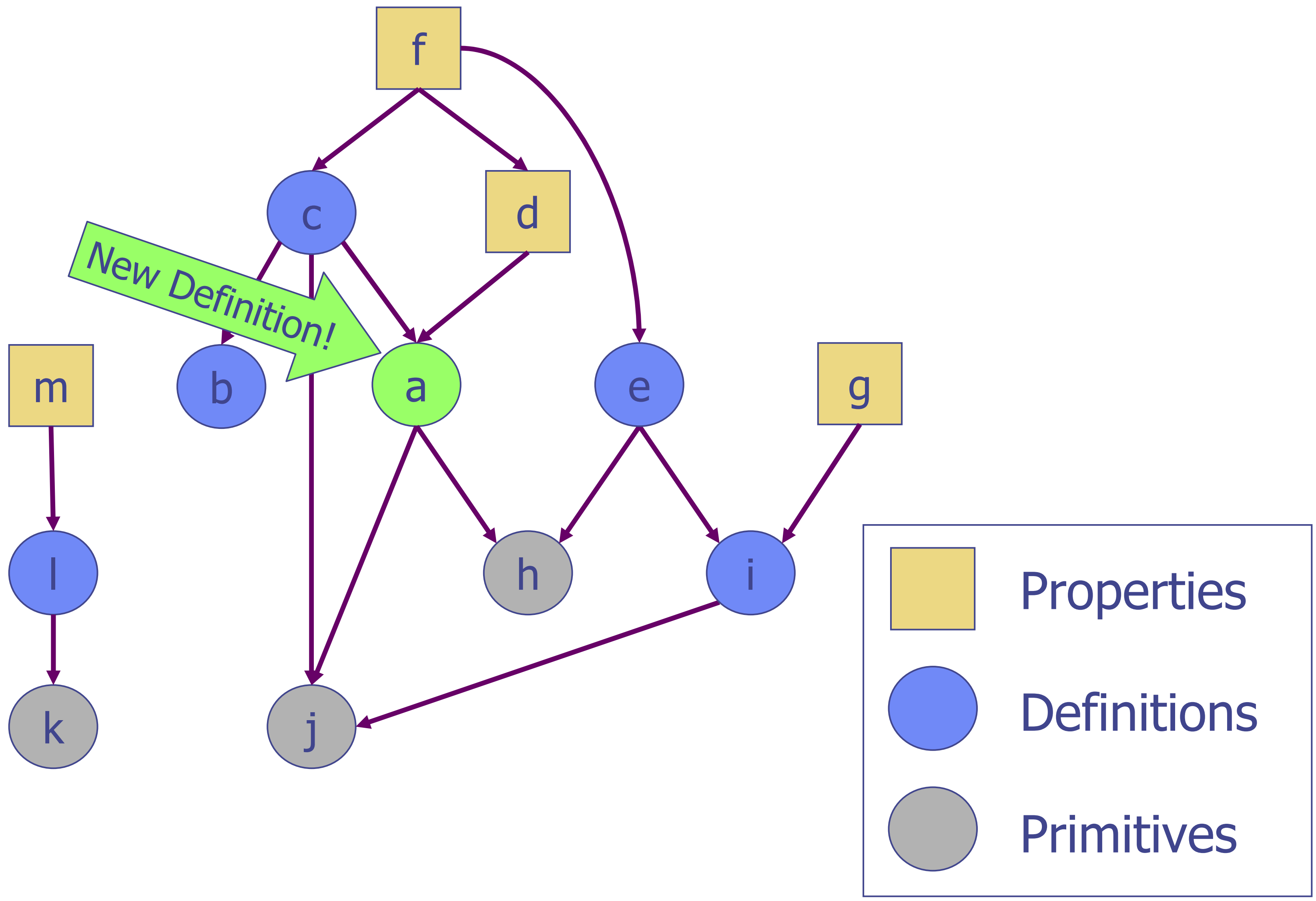
```
0cc175b9c0f1b6a831c399e269772661
92eb5ffee6ae2fec3ad71c777531578f
81a5fe3d544359af13848e6192ece475
445a4ca24e10824e03ef42e2e1d755d9
987dd8f5f1293857dc7932c14c7f3d80
8b3ee2a3933b9c01878bcddc298ff9e2
bb53046df3ef7793ee7c37aec0d090d0
ad797e6f29cf558f7aeb8200563ecd3a
8959f36e873441e58dcc9222777b6d47
84de7ff93b201e8c5b4cf0e006dfe848
7a5acfc765e1875a49daffd8561ae025
```

- If we find a definition whose hash is not listed, then it must be new/modified.

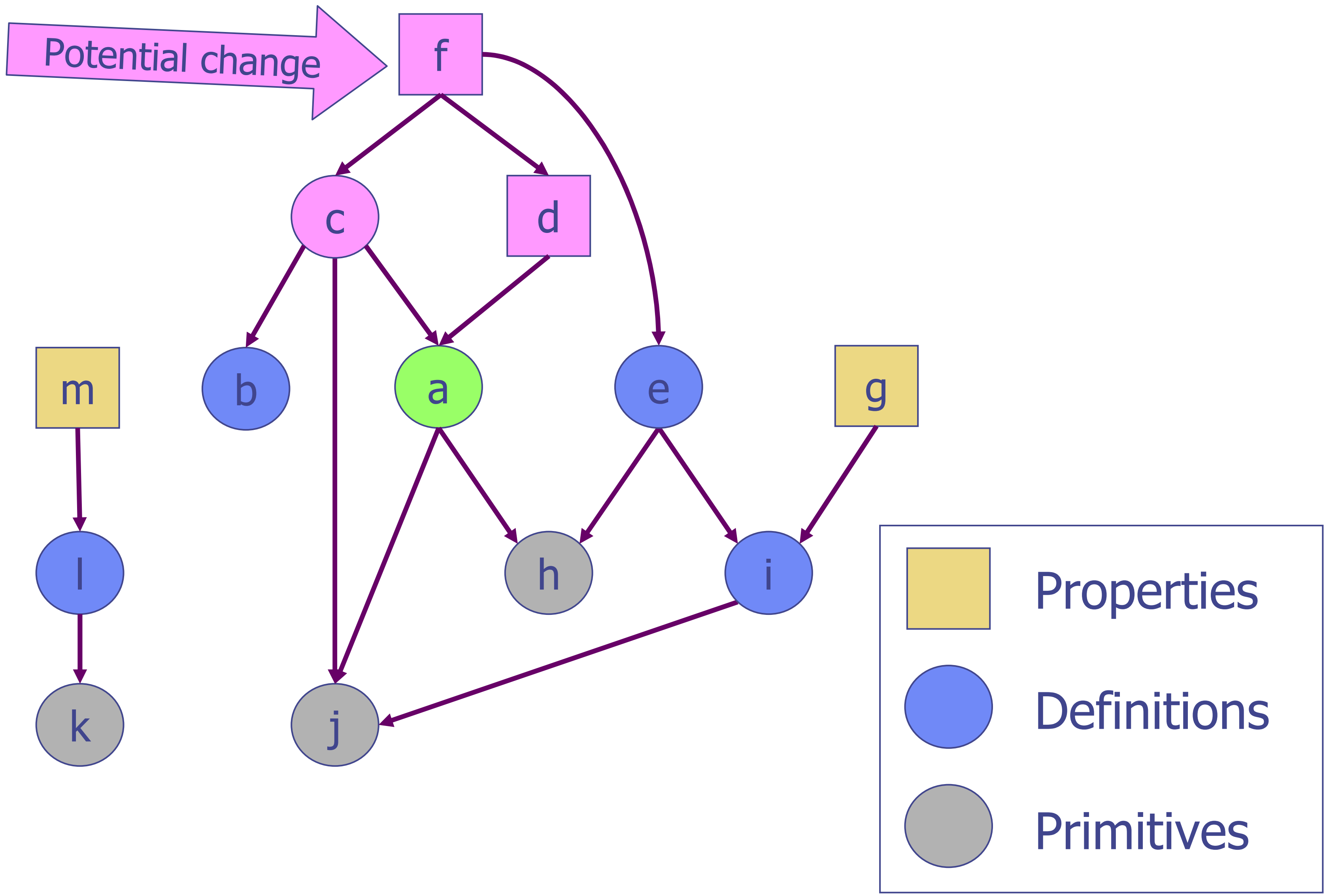
Using a Dependency Graph:



Using a Dependency Graph:



Using a Dependency Graph:



Benefits of Hashing:

- Fine-grained dependency analysis reduces the cost of reconstructing evidence after the program has been modified

- By hashing over abstract syntax, we do not flag any changes if the source text is reformatted, if comments are changed, etc…

Management Activities:

Evidence management tools let users ask (and answer) questions like the following:

- What properties have I verified (or not)?
- What tools did I use?
- Is the evidence up to date & consistent with the code?
- What other verification strategies should I pursue?
- Where am I most vulnerable?
- What should I do next?

Scoring & prioritization mechanisms required

Summary:

- Solid foundations:
  - Precise, formal semantics for Haskell
  - A sound & expressive programming logic, P-logic
- Extensible tools:
  - A flexible infrastructure for certification
  - A small but growing collection of servers
- A vision for high-assurance development:
  - Extends & integrates current methodologies
  - An evolution path for applying formal methods