Achieving Architectural Control via Language Support for Capabilities

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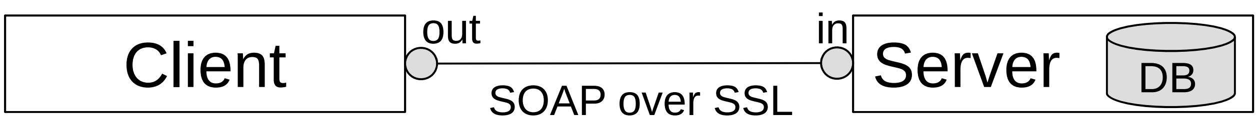
Do You Control Your Architecture?

- ***Architectural Control*** [AOPL14] is the ability of the software architect to:
  - **Specify** architectural constraints sufficient to ensure system properties
  - **Enforce** those constraints as the system is built and evolved

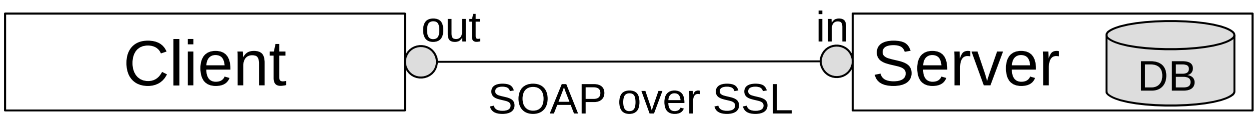
- Distributed system example:



- Is the architecture followed consistently in the system?
  - Does the implementation always use SSL?
  - Does the implementation add any hidden connections?
  - Does the client access the disk, or is it stateless (as shown)?

Architectural Control is Hard

- Distributed system example in Java



- In Java code, is SSL used consistently? Are there other connections?
  - Does dynamically loaded code use the network?
  - What about third party libraries, or native code?
- Many architectural properties similarly depend on use of resources
  - Network, storage, etc. – if the OS controls it, the architect may want to also
- Today constraints are enforced (imperfectly) via software process
  - Each developer must know and follow the architectural rules during evolution
  - Assuring third-party code is difficult
    - Sandboxing is one possible technique – but difficult and error-prone in practice [CMD+15]

A Vision: Own Your Architecture

1. Resource architecture
   - A specification of which modules can use key resources
     - Example: only the Middleware module can use the network
   - Resources include I/O and global state, but additional resources can be defined
   - Enforced by built-in language mechanisms

Capabilities [DV66]

2. Delegate enforcement of properties
   - Owners of modules that access the relevant resource
     - Example: the architect discusses important communication invariants with the middleware lead, and important storage invariants with the database lead

3. Keep architecture under version control
   - Architect approves all changes
     - Example: if a developer requests access to the network, the architect can approve—or more likely, tell the developer to use the existing middleware library

Capability-Based Resource Control

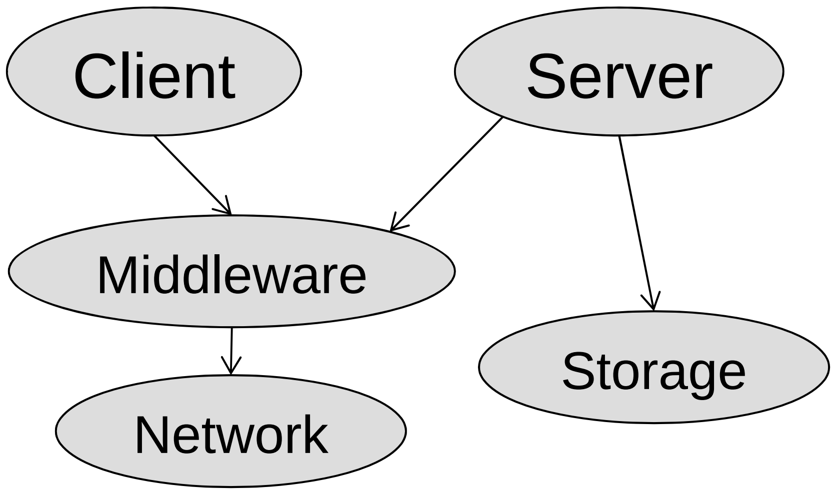
Is **owning** the architecture sufficient to **control it**?

- What if the Client opens other, unsecured, connections?

Conceptual Architecture [SG94]

Solution: resources as **capabilities**

- Capability: an unforgeable token controlling access to a resource [DV66]
- No ambient capabilities
  - By default, Client and Server have no network capability
- Capability delegation
  - Explicitly pass capabilities to modules, such as Middleware, that need them



Capability/Object Structure

Capability-Safe Languages [Mil06]

- A language in which an object can only get a capability if it is explicitly given one

- Restrictions
  - No ambient authority – resources unavailable without a capability
    - E.g. cannot simply import java.io.* and then open a file
  - No global mutable state – would allow anyone to get/put capabilities
    - Global variables are OK if they hold transitively immutable values
  - Prior work: E, Joe-E, …

Capability-Safe Languages

- A language in which an object can only get a capability if it is explicitly given one

- Our research
  - A way to achieve architectural control via capabilities (outlined above)
    - Future work: validation, extension to IDEs and other tools
  - A capability-safe **module system**
    - Reconciles conveniences of typical module systems with capability safety
  - A **formalization** of capabilities in the presence of mutable state
    - Clarifies the role of mutable state in capability safety
  - A refined, **non-transitive notion of authority**
    - Supports informal reasoning about capability restriction
    - Future work: formalize this reasoning
  - Design principles for **capability-safe type systems** and **reflection**
    - Prior work focused on dynamically typed languages (E) or adapting existing designs (Joe-E)

Capability-Safe Module System

```
module Lists
  type List
    ...
  def create():List
    ...

resource module UserInfo
  import Lists
  var name : String = 'EMPTY'
  def init(uName : String) : Unit
    name := uName
    var actionHistory : Lists.List = Lists.create()
    ...
  def getName() : String = name
    ...


resource module DocumentLock
  require SigUserInfo as uInfo
  def sign() : Boolean =
    var signee : String = uInfo.getName()
    ...
  ...

resource module Main
  instantiate UserInfo() as uInfo
  instantiate DocumentLock(uInfo) as docLock
  ... // client code
```

Resource modules capture state or I/O;
Pure modules don't

Pure modules can be imported freely;
Resource modules must be required parameters of the client module

A resource module can be instantiated, passing in parameters (if any)
(*cf.* ML, Units, Newspeak, etc.)

Capability-Safe Module System

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  type List
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  def create():List
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resource module UserInfo
  import Lists
  var name : String = 'EMPTY'
  def init(uName : String) : Unit
    name := uName
    var actionHistory : Lists.List = Lists.create()
    ...
  def getName() : String = name
    ...


resource module DocumentLock
```

```
  def init(uName : String) : Unit
    name := uName
    var actionHistory : Lists.List = Lists.create()
    ...
  def getName() : String = name
    ...


resource module DocumentLock
  require SigUserInfo as uInfo
  def sign() : Boolean =
    var signee : String = uInfo.getName()
    ...
  ...

resource module Main
  instantiate UserInfo() as uInfo
  instantiate DocumentLock(uInfo) as docLock
  ... // client code
```

I/O Capabilities

```
resource module Main
  require FFI
  instantiate FileIO(FFI)
  instantiate Logger(FileIO)
  instantiate Client(Logger)
```

The OS passes a foreign function interface (FFI) capability to Main

The FFI capability is used to instantiate the I/O module

We can restrict the FileIO capability by implementing a logging facility on top of it

The Client can write information to the log, but assuming Logger is implemented securely, it cannot do any other File I/O.

Note: the security of Logger can be verified simply by inspecting the Logger type!

Capability-Safe Modules: Discussion

- Resource modules are like Newspeak, or Units
  - Can only be instantiated or passed as parameters
  - Syntax as convenient as Java import from within a module
  - Slightly less convenient for clients that must instantiate/pass resource modules—but permits more reasoning in exchange

- Pure modules are unrestricted, as in Java
  - Hopefully lower cost overall relative to Newspeak/Units

- Main can require the foreign function interface (FFI)
  - It then passes the FFI capability to I/O modules
  - Shortcut: also OK for main to require modules that take only the FFI as a parameter

Demo

A Capability-Safe Object Calculus

$$
\begin{array}{lcl}
e & ::= & x \\
 & | & \texttt{new}_s(x \Rightarrow \overline{d}) \\
 & | & e.m(e) \\
 & | & e.f \\
 & | & e.f = e \\
 & | & \texttt{bind}\ x = e\ \texttt{in}\ e \\
s & ::= & \texttt{stateful} \mid \texttt{pure}
\end{array}
\qquad
\begin{array}{lcl}
d & ::= & \texttt{def}\ m(x : \tau) : \tau = e \\
 & | & \texttt{var}\ f : \tau = x \\
\tau & ::= & \{\overline{\sigma}\}_s \\
\sigma & ::= & \texttt{def}\ m : \tau \to \tau \\
 & | & \texttt{var}\ f : \tau
\end{array}
$$

- Calculus includes objects, methods, mutable fields
- Structural object types
  - `stateful` (have mutable fields/capture state) or `pure`
  - A `stateful` type is a supertype of the equivalent `pure` type
- A `bind` construct for module translation
  - restricts the environment of the second expression to contain only the variable x – *cf.* Scala's Spores [MHO14]

A Capability-Safe Object Calculus

$$\Gamma_{stateful} = \{x : \{\overline{\sigma}\}_{\texttt{stateful}} \mid x : \{\overline{\sigma}\}_{\texttt{stateful}} \in \Gamma\}$$

$$\frac{\Gamma_{pure} = \Gamma \setminus \Gamma_{stateful} \qquad \Gamma_{pure},\ y : \tau_1 \mid \Sigma \vdash^{z} e : \tau_2}{\Gamma \mid \Sigma \vdash_{\texttt{pure}} \texttt{def}\ m(y : \tau_1) : \tau_2 = e \ : \ \texttt{def}\ m : \tau_1 \to \tau_2} \ (\textsc{DT-DefPure})$$

$$\frac{\Gamma,\ x : \tau_1 \mid \Sigma \vdash^{z} e : \tau_2}{\Gamma \mid \Sigma \vdash^{z}_{\texttt{stateful}} \texttt{def}\ m(x : \tau_1) : \tau_2 = e \ : \ \texttt{def}\ m : \tau_1 \to \tau_2} \ (\textsc{DT-DefStateful})$$

$$\frac{\Gamma \mid \Sigma \vdash^{z} x : \tau}{\Gamma \mid \Sigma \vdash^{z}_{\texttt{stateful}} \texttt{var}\ f : \tau = x \ : \ \texttt{var}\ f : \tau} \ (\textsc{DT-VarX})$$

- Key rule DT-DefPure removes `stateful` variables from the context when checking a `pure` method
- DT-VarX is only valid in `stateful` objects

Translating Modules to the Calculus

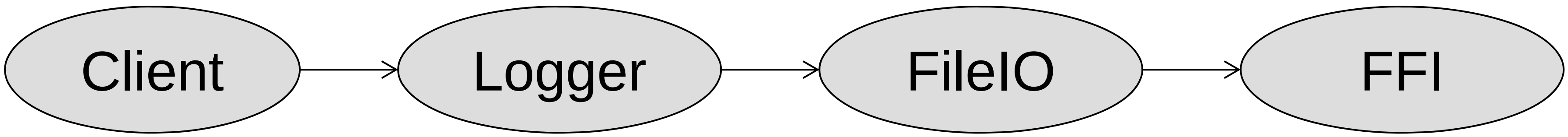
```
resource module Main
  require FFI
  instantiate FileIO(FFI)
  instantiate Logger(FileIO)
  instantiate Client(Logger)
  ...
```

```
def Main(ffi:FFI):Tmain
  bind
    ffi = ffi
    FileIO = FileIO
    Logger = Logger
    Client = Client
  in let
    fio = FileIO(ffi)
    log = Logger(fio)
    client = Client(log)
  in ...
```

- Modules with require become functions (cf. functors)
- bind is used to bind only the imported modules
- instantiate appropriate modules by applying functions

Note: some details simplified for presentation

The Nature of Authority



- What is the authority of Client?
  - given reasonable implementations of Logger/FileIO abstractions
- Prior work's answer: Logger, FileIO, and FFI
- But we argue that Client can only log
  - It cannot do arbitrary File I/O, let alone call arbitrary foreign functions
  - Authority should be viewed as non-transitive
    - There is File IO going on, but it is being done by the Logger
    - Client's authority is only to Logger, unless/until Logger returns a FileIO reference to the Client
  - Enables reasoning about *authority restriction*
    - Logger restricts the FileIO capability to only support logging
    - Future work: additional type system support for this

Authority Safety

- Definition of Authority: the objects I can access directly
  - In my fields
  - Captured in the scope of my methods
- Theorem [Authority Safety]: the authority of an object o increases (by adding an object v) only when:
  - o creates a new object value v
  - A method of o is invoked, passing an argument value v
  - A method that o invoked returns, returning a value v
- Practical consequence:
  - Can reason about an object's authority via calls to its interface
  - **Modules are objects**, so this applies to modules, too
    - Nothing special is needed to handle **dynamically loaded modules**

Type Tests and Capability Safety

```
class BaseLogger
  def log(s:String)
```

```
class ExposedLogger
    extends BaseLogger
  def getLogFile():File
```

```
if (log instanceof ExposedLogger)
  ((ExposedLogger) log).getLogFile().delete()
```

- Would like interface to restrict operations we can perform
  - But downcasts are a problem
- Wyvern's design
  - Structural types: no downcasts possible
  - Datatypes: fixed set of subtypes
    - Pattern matching is OK – can enumerate all possibilities
  - Open tagged types [LASP15]
    - Also allow pattern matching downcasts
    - Lose reasoning about interface—but only when this construct is used
    - Contrast Java – every non-`final` type is open and tagged

Capability-Safe Reflection

```
val m:ObjectMirror = reflect(baseLogger)
val log:ObjectMirror = m.invoke(“getLogFile”)
log.invoke(“delete”)
```

- Reflection can potentially violate capability safety
  - Above: can invoke hidden method on baseLogger
- Safe reflection in Wyvern – universally available
  - Only provides access to methods visible when the mirror was obtained
  - Can’t do anything with reflection that you can’t do without it
  - A reflection capability can be restricted to a narrower type
- Unsafe reflection also provided
  - Access all members – useful for debugging
  - This reflection is available only as a resource module
    - Thus subject to the architectural control mechanisms described above

Capability-Based Architectural Control

How can I enforce key architecture properties?

- **Own your architecture**
  - Architecture specification under source control
  - Use capabilities to delegate resource access in a limited way
- **Use a capability-safe language**
  - Treat resource modules as capabilities – distinct in type system
  - Non-transitive authority for capability restriction
  - Design of type tests and reflection enhances type-based reasoning

Coming your way soon as part of the Wyvern project

- Thanks: NSA Lablet, DARPA BRASS program