Fugue: Annotations for Protocol Checking

Reading: ***The Fugue Protocol Checker: Is Your Software Baroque?***

17-654/17-765
Analysis of Software Artifacts
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Find the Bug!

```
void CopyFile (string src, string dest)
{
  StreamReader fromFile = new StreamReader(src);
  StreamWriter toFile = new StreamWriter(dest);
  string line;
  while ((line = fromFile.ReadLine()) != null) {
    toFile.WriteLine(line);
  }
  fromFile.Close();
  ERROR: warning: StreamWriter resource 'toFile' becoming unreachable
  without calling StreamWriter.Close
}
```

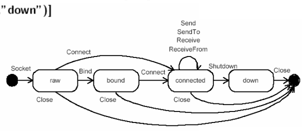
Find the Bug!

```
static public string DoSocketGet (string server)
{
  Socket s = new Socket(AddressFamily.InterNetwork, SocketType.Stream, ProtocolType.Tcp);
  byte[] cmd = Encoding.ASCII.GetBytes("GET / HTTP/1.1\r\nHost: " +
     server + "\r\nConnection: Close\r\n\r\n");
  s.Send(cmd);
  ERROR: cannot call Socket.Send because 's' in state 'raw', but expected
  state 'connected'; did you forget to call Socket.Connect?
  // ...
}
```

Specifications(1)

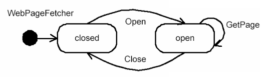
```
class StreamWriter
{
  [Creates]
  StreamWriter (string filename);

  [Disposes]
  void Close ();
}
```

Specifications(2)



```
[WithProtocol("raw","bound","connected","down")]
class Socket
{
  [Creates("raw")]
  public Socket (...);

  [ChangesState("raw", "bound")]
  public void Bind (EndPoint localEP);

  [ChangesState("raw", "connected"),  ChangesState("bound", "connected")]
  public void Connect (EndPoint remoteEP);

  [InState("connected")]
  public int Send (...);

  [InState("connected")]
  public int Receive (...);

  [ChangesState("connected", "down")]
  public void Shutdown (SocketShutdown how);

  [Disposes(State.Any)]
  public void Close ();
}
```

Specifications(3)



```
[WithProtocol("open", "closed")]
class WegPageFetcher
{
  [InState("connected", WhenEnclosingState="open"), NotAliased(WhenEnclosingState="open")]
  [Unavailable(WhenEnclosingState="closed")]
  private Socket socket;

  [Creates("closed")]
  public WebPageFetcher () { }

  [ChangesState("closed","open")]
  public void Open (string server)
  {
    Socket newSock = new Socket( AddressFamily.InterNetwork, SocketType.Stream,
                                 ProtocolType.Tcp);
    this.socket = newSock;
    IPAddress host = Dns.Resolve(server).AddressList[0];
    socket.Connect(new IPEndPoint(host, 80));
  }

  [InState("open")]
  public string GetPage (string url)
  {
    this.socket.Send( Encoding.ASCII.GetBytes("GET / HTTP/1.1\r\nHost: " +
                                              server + "\r\nConnection: Close\r\n\r\n"));
    //...
  }

  [ChangesState("open", "closed")]
  public void Close ()
  {
    this.socket.Send(Encoding.ASCII.GetBytes("QUIT\r\n"));
    this.socket.Close();
  }
}
```

Aliasing Challenges

a.Open(); b.Open();

- Legal only if a != b

Fugue Alias Analysis

- Annotations
  - NotAliased
    - Field or param is unique pointer to an object
    - Allows type system to track state changes
    - Warning (lost track of object) if assigned to Escaping parameter
  - MayBeAliased
    - May have aliases
    - May not call state-changing functions
    - If not escaping, error if assigned to field or passed to Escaping parameter
  - Escaping
    - A MayBeAliased parameter that may be (transitively) assigned to a field

Fugue Alias Analysis

- Analysis information
  - Environment env: var → addr
  - Capabilities: addr → aliasInfo
  - aliasInfo: one of NotAliased, MayBeAliased, MayBeAliased/Escaping

Example: Alias Analysis

```
void f([MayBeAliased][Escaping] x);
void g([MayBeAliased] x);
```

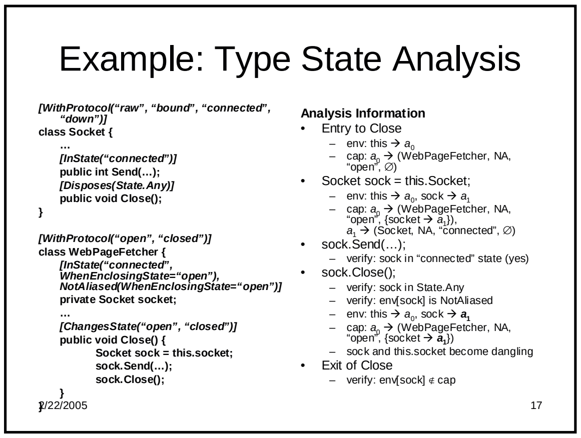
	Environment	Capabilities
void h([NotAliased] y) {	y → *a*	*a* → NA
z = y;	y → *a*, z → *a*	*a* → NA
v = new T();	y→*a*, z→*a*, v→*b*	*a*→NA, *b*→NA
g(z);	y→*a*, z→*a*, v→*b*	*a*→NA, *b*→NA
	a still NotAliased	
f(v);	y→*a*, z→*a*, v→*b*	*a*→NA, *b*→MBA
}	*Warning: lost track of b*	

Flow Functions

- init
  - initialization based on param. annotations
- x = y
  - env [x → env[y]]
- x = new T()
  - env[x → *a*]
    - *a* ∉ *domain*(cap)
  - cap[*a* → NotAliased]
- x = y.f
  - *[slightly simplified rule]*
  - env[x → *a*]
    - *a* ∉ *domain*(cap)
  - cap[*a* → *annot*(f)]
- x = f(y)
  - if cap[env[y]] == NotAliased && *annot*(f_arg)==Escaping
    warn("lost track of y")
    cap[env[y] → **MayBeAliased**]?
  - env[x → *a*]
    - *a* ∉ *domain*(cap)
  - cap[*a* → *annot*(f_return)]
- Analysis is underspecified in paper
  - How to perform joins?
  - How to model MayBeAliased params?

Type State Analysis

- Extended analysis information
- Environment
  - Symbolic address for references
  - Also stores constants (for constant prop.)
- Capabilities
  - Aliasing state
  - Symbolic object state
  - Contents of fields (symbolic addresses)

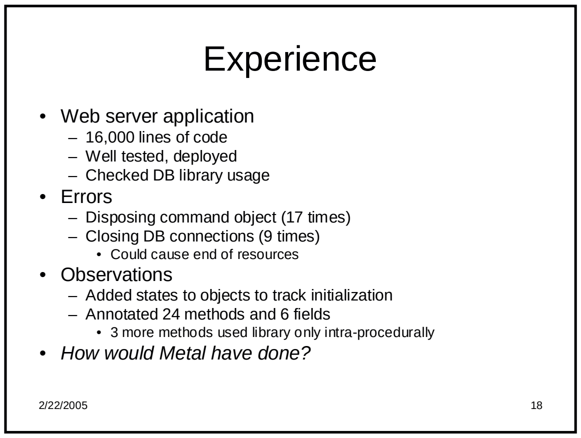


Example: Type State Analysis

```
[WithProtocol("raw", "bound", "connected",
    "down")]
class Socket {
    …
    [InState("connected")]
    public int Send(…);
    [Disposes(State.Any)]
    public void Close();
}

[WithProtocol("open", "closed")]
class WebPageFetcher {
    [InState("connected",
    WhenEnclosingState="open"),
    NotAliased(WhenEnclosingState="open")]
    private Socket socket;
    …
    [ChangesState("open", "closed")]
    public void Close() {
        Socket sock = this.socket;
        sock.Send(…);
        sock.Close();
    }
}
```

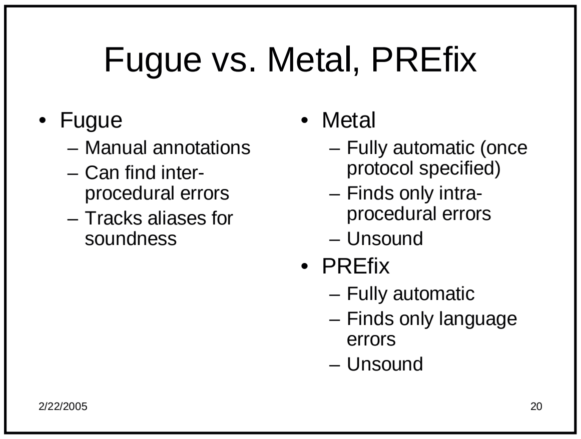
Analysis Information

- Entry to Close
  - env: this → a_0
  - cap: a_0 → (WebPageFetcher, NA, "open", ∅)
- Socket sock = this.Socket;
  - env: this → a_0, sock → a_1
  - cap: a_0 → (WebPageFetcher, NA, "open", {socket → a_1}), a_1 → (Socket, NA, "connected", ∅)
- sock.Send(…);
  - verify: sock in "connected" state (yes)
- sock.Close();
  - verify: sock in State.Any
  - verify: env[sock] is NotAliased
  - env: this → a_0, sock → $\boldsymbol{a_1}$
  - cap: a_0 → (WebPageFetcher, NA, "open", {socket → $\boldsymbol{a_1}$})
  - sock and this.socket become dangling
- Exit of Close
  - verify: env[sock] $\notin$ cap



Experience

- Web server application
  - 16,000 lines of code
  - Well tested, deployed
  - Checked DB library usage
- Errors
  - Disposing command object (17 times)
  - Closing DB connections (9 times)
    - Could cause end of resources
- Observations
  - Added states to objects to track initialization
  - Annotated 24 methods and 6 fields
    - 3 more methods used library only intra-procedurally
- *How would Metal have done?*



Fugue vs. Metal, PREfix

- Fugue
  - Manual annotations
  - Can find inter-procedural errors
  - Tracks aliases for soundness
- Metal
  - Fully automatic (once protocol specified)
  - Finds only intra-procedural errors
  - Unsound
- PREfix
  - Fully automatic
  - Finds only language errors
  - Unsound