Rule Based Static Analysis of Network Protocol Implementations

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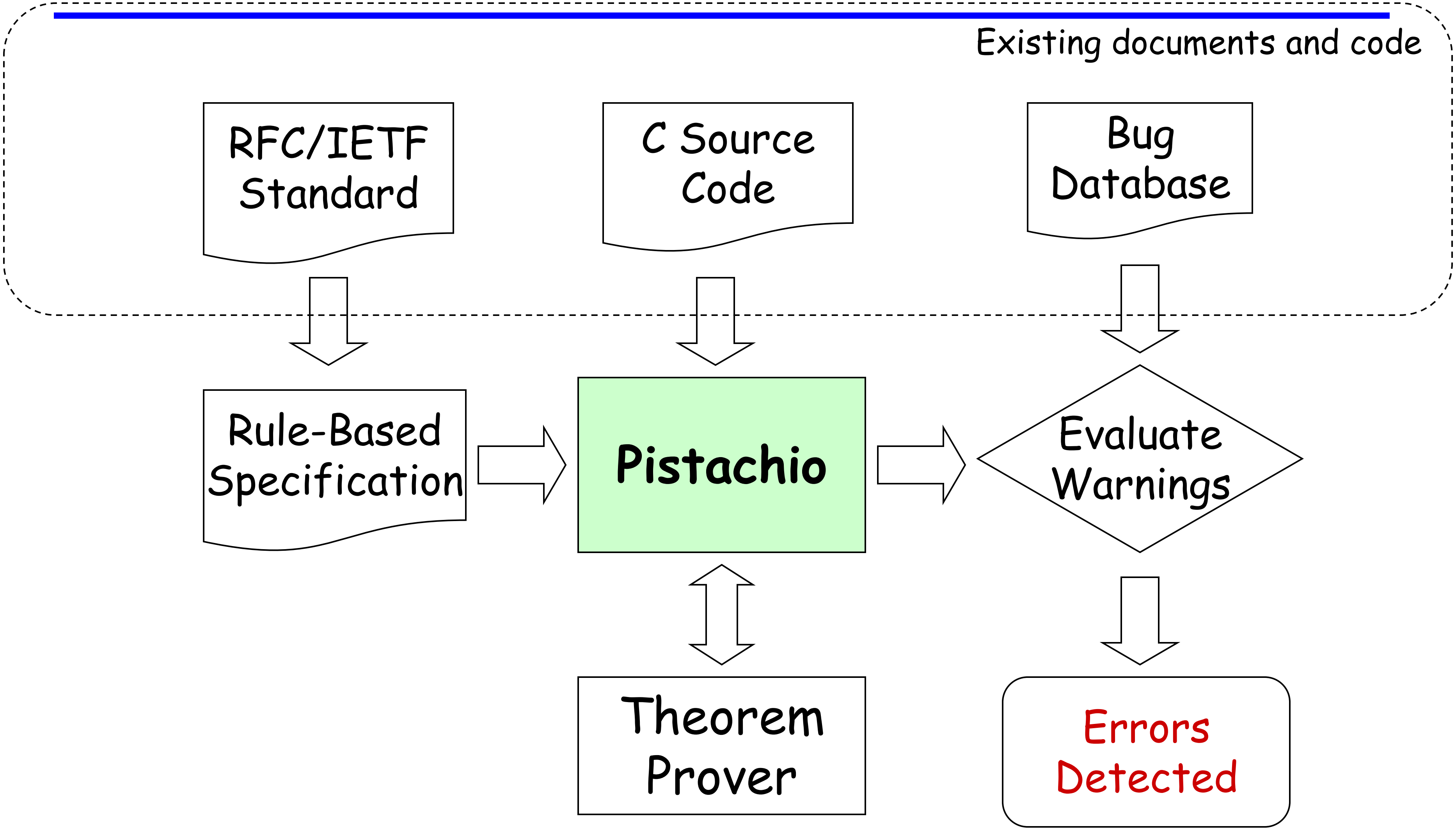
Motivation

- Network protocols must be reliable and secure

- Lots of work has been done on this topic
  - But mostly focuses on abstract protocols
  - ==> Implementation can introduce vulnerabilities

- **Goal:** Check that implementations match specifications
  - Ensure that the protocol we've modeled abstractly and thought hard about is actually what's in the code

Pistachio Architecture



Summary of Results

- Ran on LSH, OpenSSH (SSH2 implementations) and RCP
- Found wide variety of known bugs and vulnerabilities
  - Well over 100 bugs, of many different kinds
- Roughly 5% false negatives, 38% false positives
  - As measured against bug databases

A Toy Protocol

- *Alternating bit protocol*

1. Start by sending *n = 1*
2. If *n* is received, send *n + 1*
3. Otherwise resend *n*

A Toy Protocol

```
int main(void) {
  int sock, val=1, recval;
  send(sock,&val,sizeof(int));
  while(1) {
    recv(sock,&recval,sizeof(int));
      if (recval == val)
        val += 2;
      send(sock,&val,sizeof(int));
  }
}
```

- *Alternating bit protocol*

1. Start by sending *n = 1*
2. If *n* is received, send *n + 1*
3. Otherwise resend *n*

A Rule Based Specification

```
  Ø (program entry)
=>
  send(_, out, _)
  out[0..3] = 1
  n := 1
```

- *Alternating bit protocol*

1. Start by sending *n = 1*
2. If *n* is received, send *n + 1*
3. Otherwise resend *n*

A Rule Based Specification

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

- *Alternating bit protocol*

1. Start by sending *n = 1*
2. If *n* is received, send *n + 1*
3. Otherwise resend *n*

A Rule Based Specification

```
  recv(_, in, _)
  in[0..3] ≠ n
=>
  send(_, out, _)
  out[0..3] = n
```

- *Alternating bit protocol*

1. Start by sending *n = 1*
2. If *n* is received, send *n* + *1*
3. Otherwise resend *n*

Our Approach

- Use symbolic execution to simulate program execution
  - Track facts about program variables
  - Generated by assignments and branches

- Only simulate realizable paths
  - Test branch conditions using theorem prover

- Check rule conclusions hold
  - Using automatic theorem prover

1. Start by sending *n = 1*

Ø (empty hypothesis)

=>

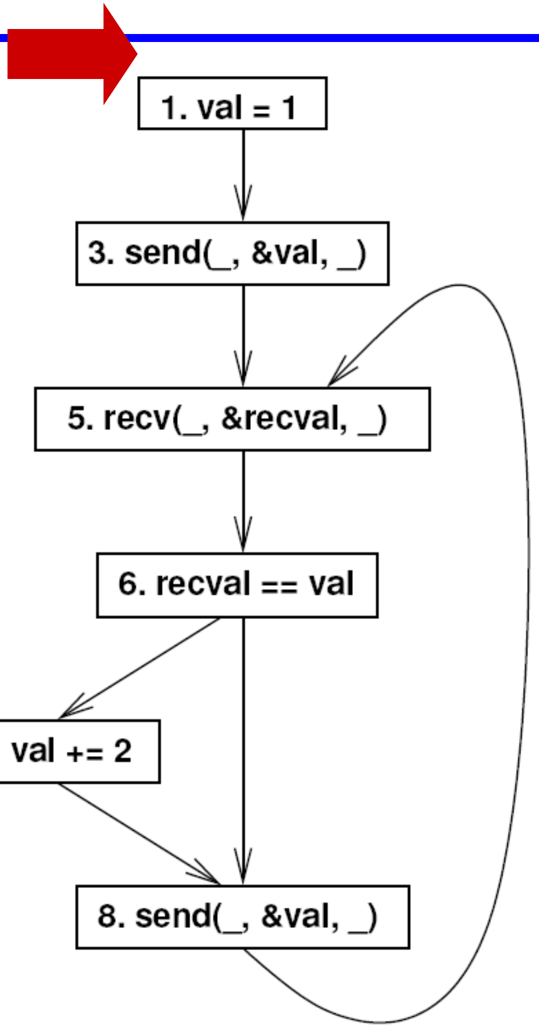
send(_, out, _)

out[0..3] = 1

n := 1

Facts: {}

Matches the empty hypothesis



1. val = 1

3. send(_, &val, _)

5. recv(_, &recval, _)

6. recval == val

7. val += 2

8. send(_, &val, _)

1. Start by sending *n = 1*

Ø (empty hypothesis)

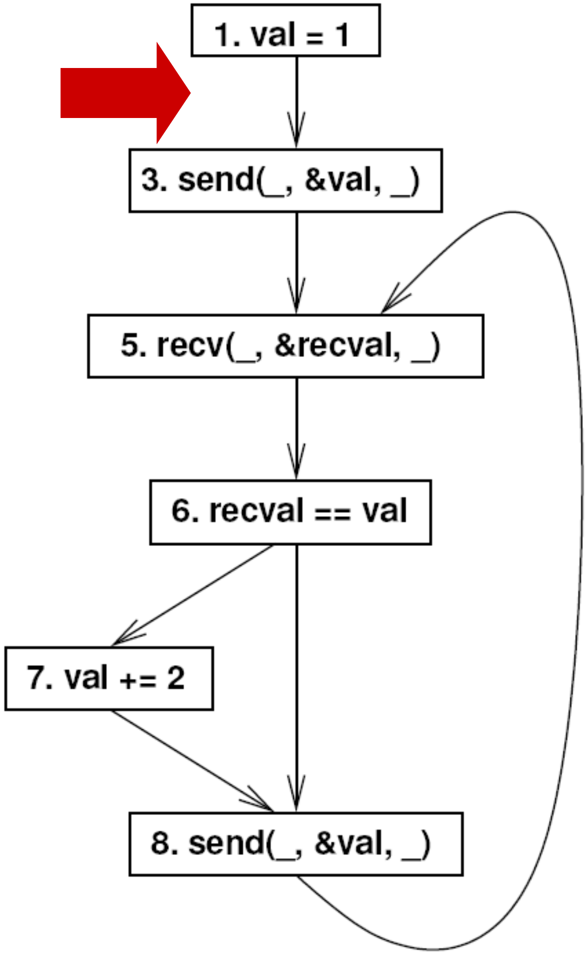
=>

send(_, out, _)

out[0..3] = 1

n := 1

Facts: {val = 1}



1. Start by sending *n = 1*

Ø (empty hypothesis)

=>

send(_, out, _)

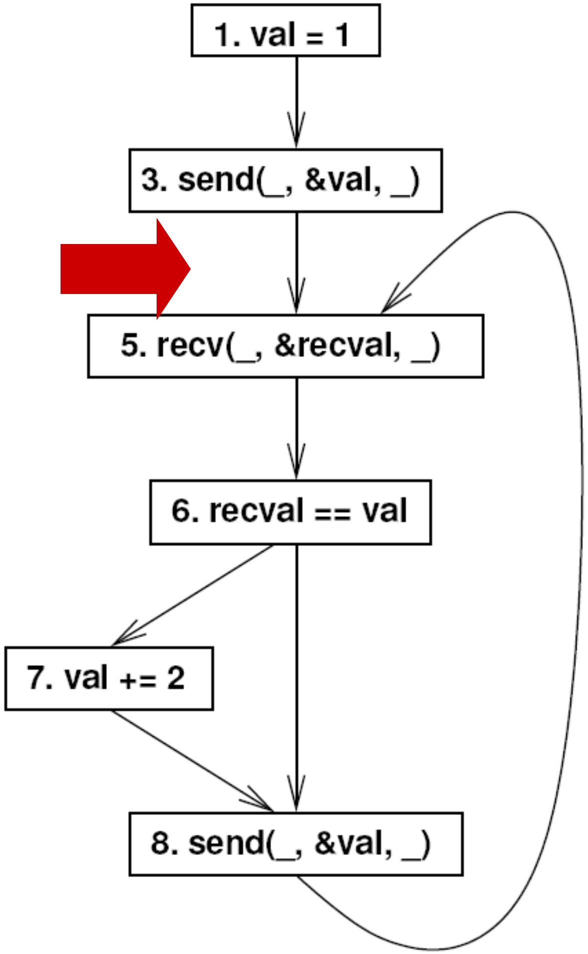
out[0..3] = 1

n := 1

Facts: {val = 1, out = &val}

Show: (val = 1) Λ (out = &val)
→ (out[0..3] = 1)

Action: n := 1



3. Otherwise resend *n*

recv(_, in, _)

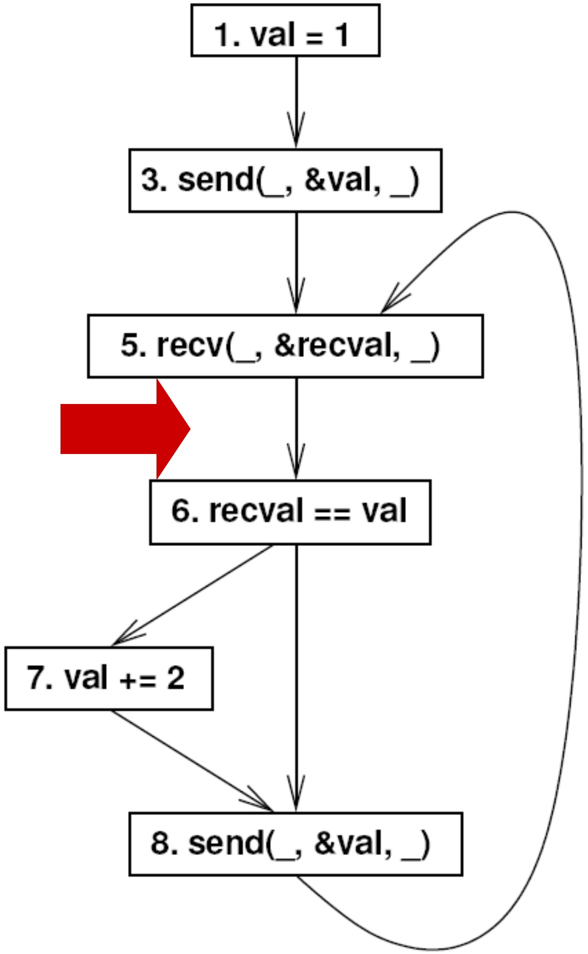
in[0..3] ≠ n

=>

send(_, out, _)

out[0..3] = n

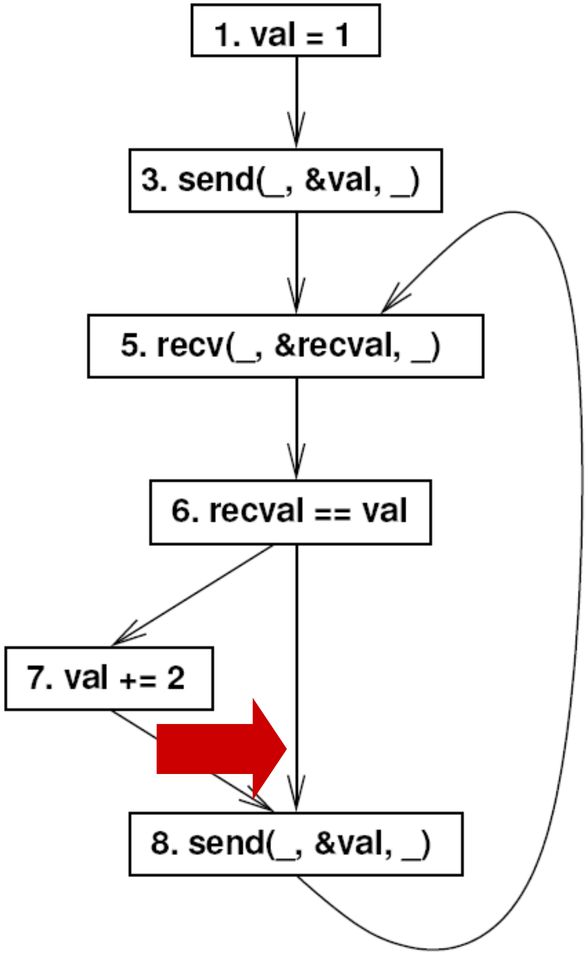
Facts: {val = 1, n = 1, in = &recval,
in[0..3] ≠ n }



3. Otherwise resend *n*

recv(_, in, _)
in[0..3] ≠ n
=>
send(_, out, _)
out[0..3] = n

Facts: {val = 1, n = 1, in = &recval,
in[0..3] ≠ n, recval ≠ val }



3. Otherwise resend *n*

recv(_, in, _)

in[0..3] ≠ n

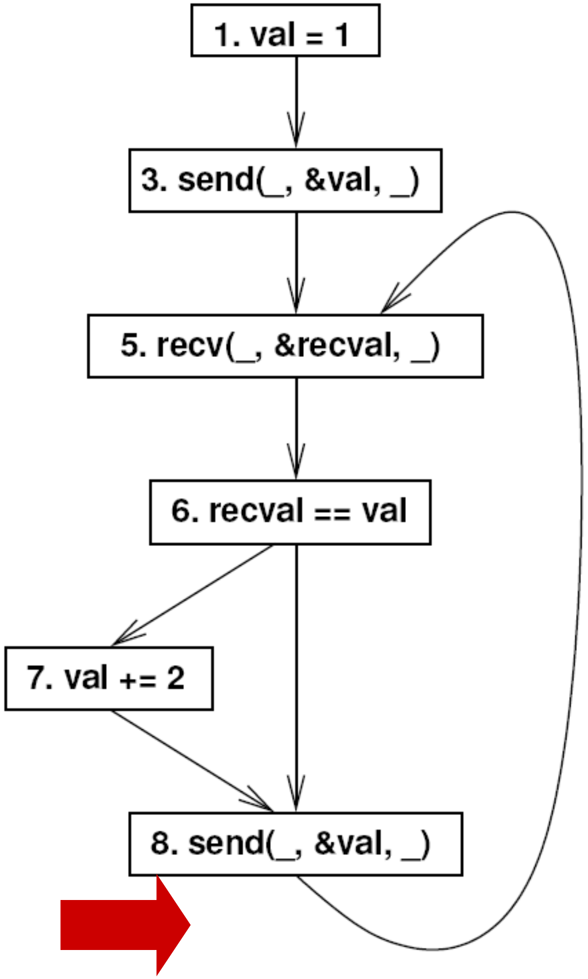
=>

send(_, out, _)

out[0..3] = n

Facts: {val = 1, n = 1, in = &recval,
in[0..3] ≠ n, recval ≠ val,
out = &val }

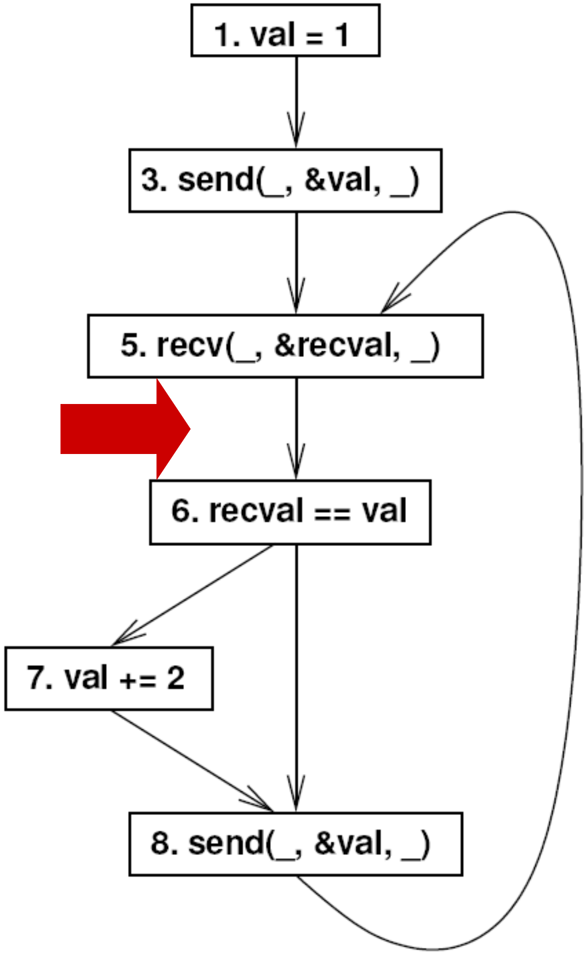
Show: out[0..3] = n



2. If *n* is received, send *n + 1*

recv(_, in, _)
in[0..3] = n
=>
send(_, out, _)
out[0..3] = in[0..3] + 1
n := out[0..3]

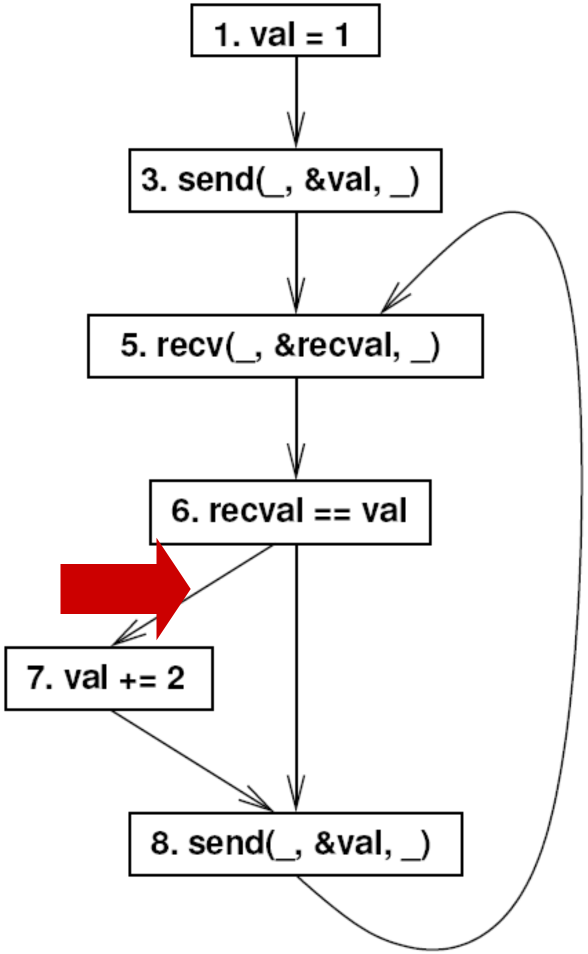
Facts: {val = 1, n = 1, in = &recval,
in[0..3] = n}



2. If *n* is received, send *n + 1*

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

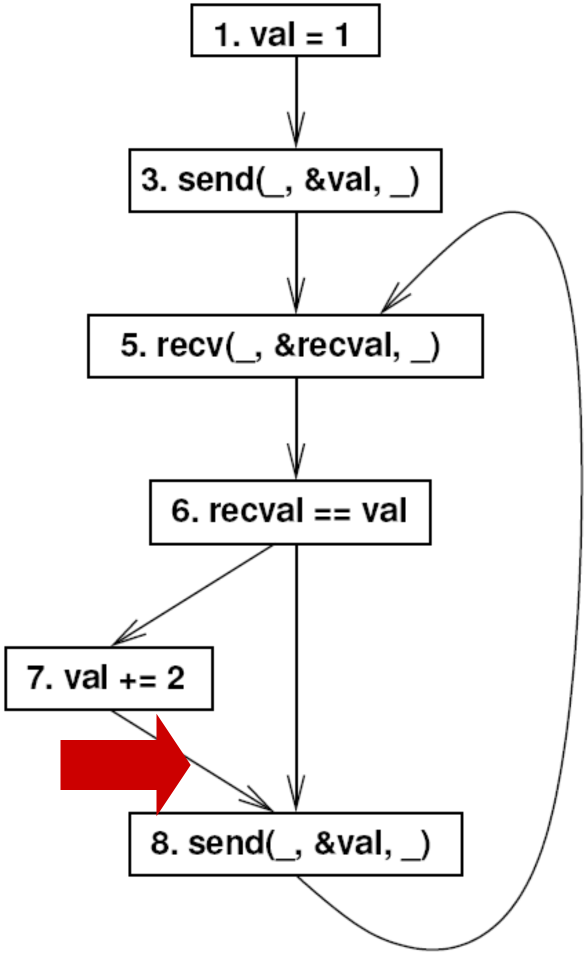
Facts: {val = 1, n = 1, in = &recval, in[0..3] = n, recval = val}



2. If *n* is received, send *n + 1*

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

Facts: {val = 3, n = 1, in = &recval,
in[0..3] = n}



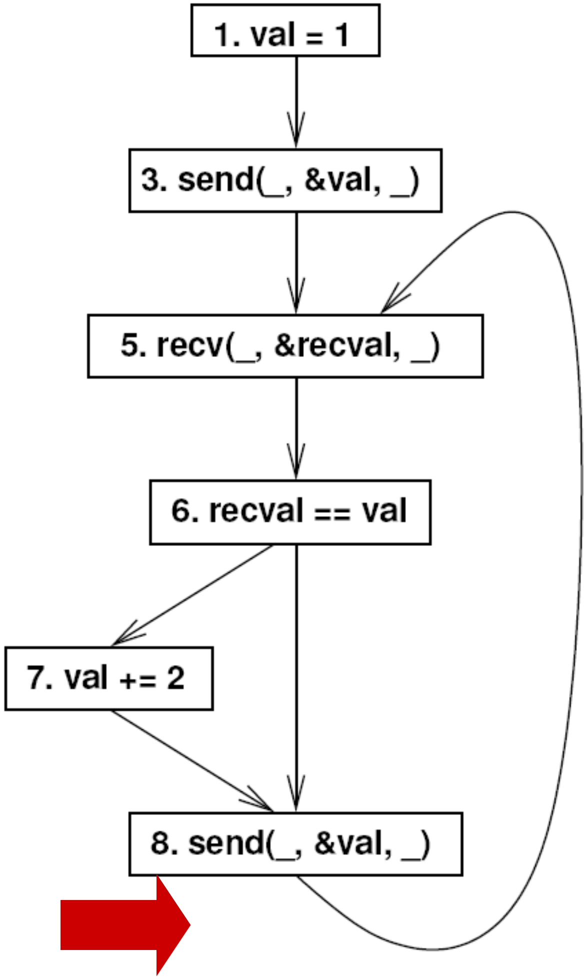
2. If *n* is received, send *n + 1*

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

Facts: {val = 3, n = 1, in = &recval,
in[0..3] = n, out = &val}

Show: out[0..3] = in[0..3] + 1

Fails to verify!



How Much State to Keep?

- One option: Keep all knowledge of state

- Need to retain old information at assignment statements
  - {val = 1, x = val} val = 2; {val = 2; x = val’; val’ = 1}

- Need to be *path-sensitive*
  - { } y = 1; if (p) then x = 1 else x = 2 { y=1; p=>(x=1); !p=>(x=2) }

- These are both expensive!

Pistachio’s Design

- Maintain *must* facts
  - Subset of true facts; ones that definitely hold
  - Implies always safe to take subset

- Kill facts at assignments
  - {val = 1, x = val} val = 2; {val = 2}

- Intersect facts at join points
  - { } y = 1; if (p) then x = 1 else x = 2 { y = 1 }

- Much more efficient
  - Loses precision
  - Aliasing issues cause some unsoundness

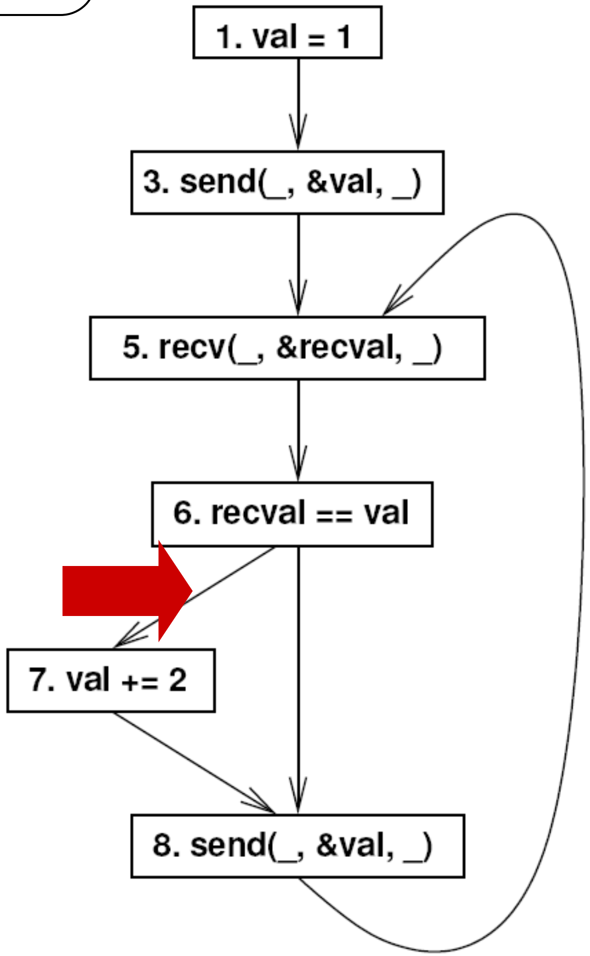
Fact substitutio

val is *killed* in the next statement

recv(_, in, _)
in[0..3] = n
=>
send(_, out, _)
out[0..3] = in[0..3] + 1
n := out[0..3]

Facts: {val = 1, n = 1, in = &recval,
in[0..3] = n, recval = val,
}

Using substitution, *recval* will still have a value of 1

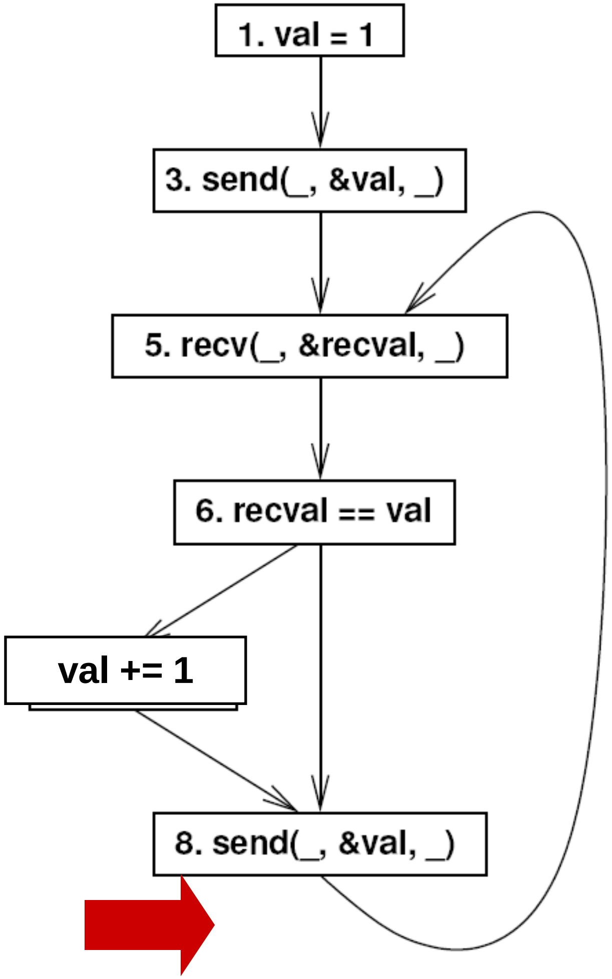


Fixpoint Example

recv(_, in, _)
in[0..3] = n
=>
send(_, out, _)
out[0..3] = in[0..3] + 1
n := out[0..3]

Facts: {val = 2, n = out[0..3],
in = &recval, in[0..3] = n,
recval = 1, out = &val,
n = val, n = 2}

by substitution



Fixpoint Example

recv(_, in, _)

in[0..3] = n

=>

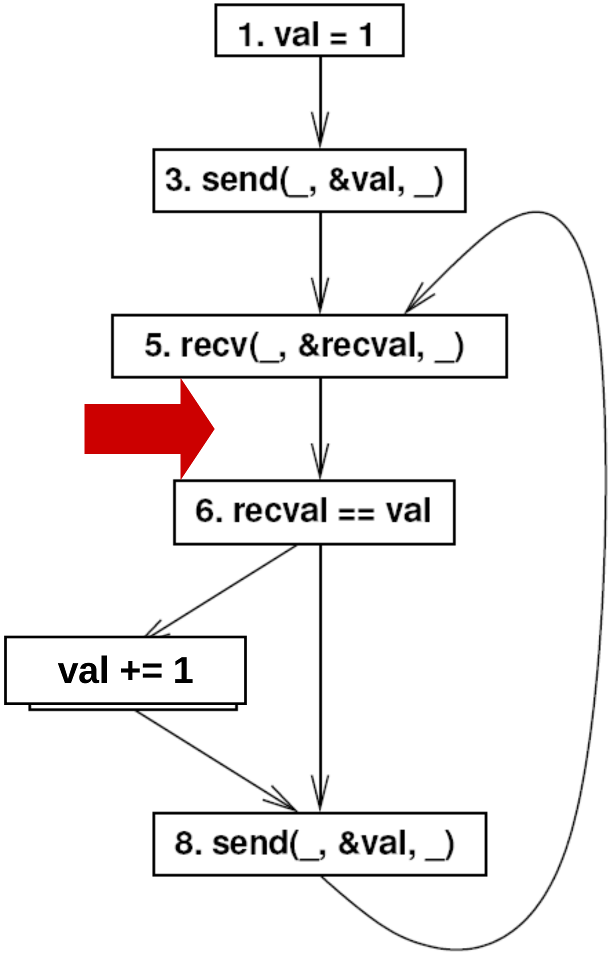
send(_, out, _)

out[0..3] = in[0..3] + 1

n := out[0..3]

Facts: {in = &recval, in[0..3] = n,
n = val}

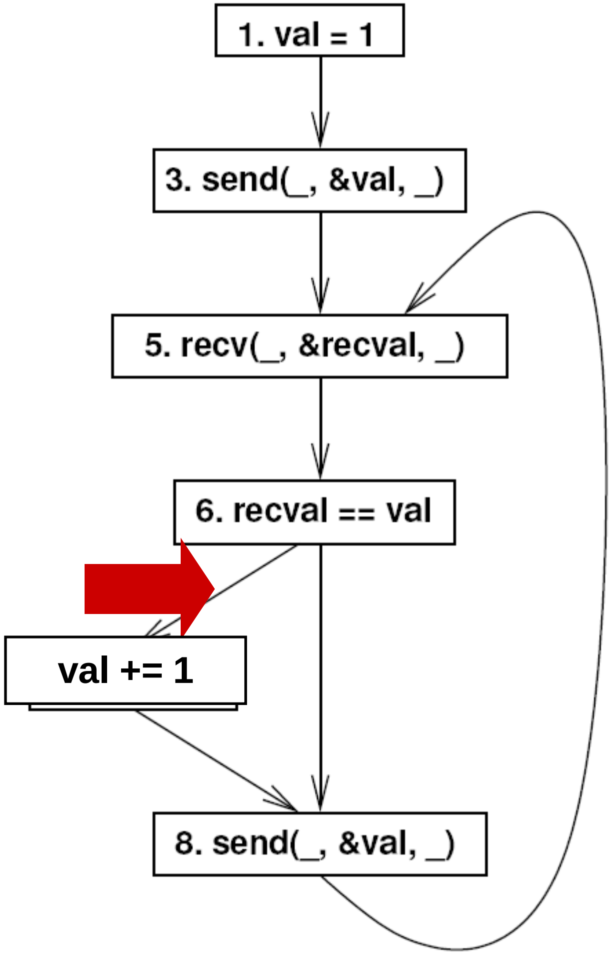
We start the loop again with the intersection of the sets of facts from the first two iterations



Fixpoint Example

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

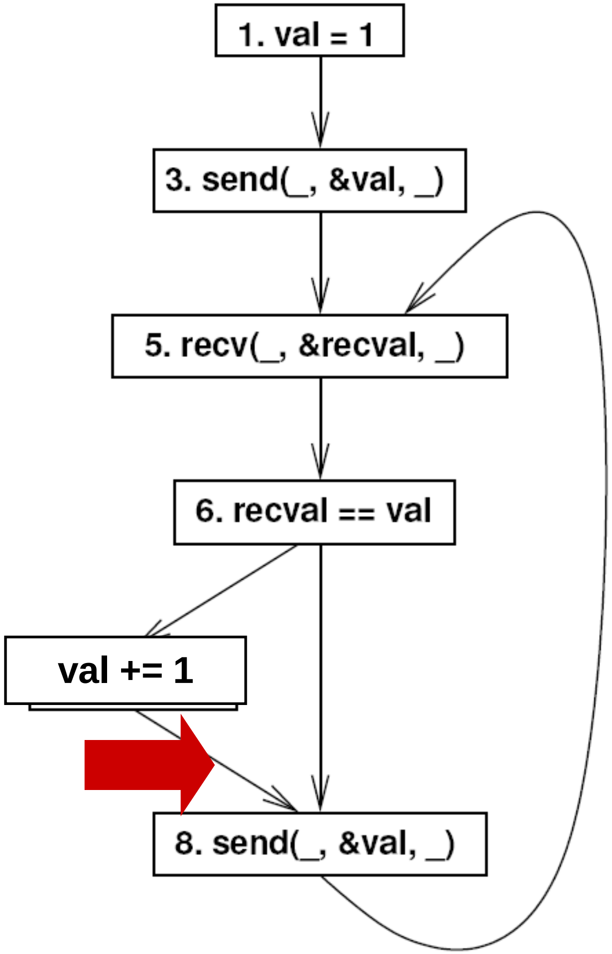
Facts: {in = &recval, in[0..3] = n,
n = val, recval = val}



Fixpoint Example

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

Facts: {in = &recval, in[0..3] = n,
val = n + 1, recval = val}



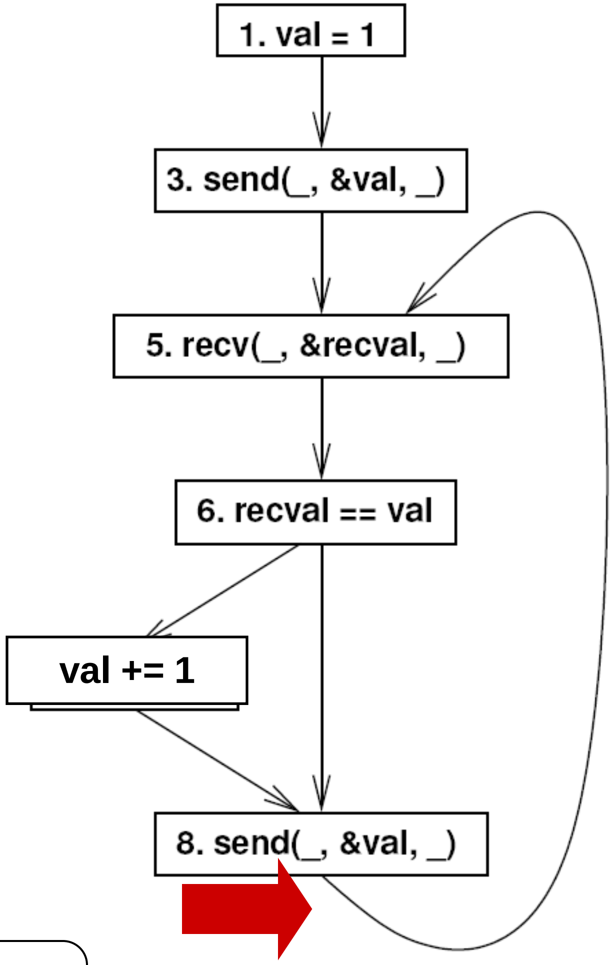
Fixpoint Example

```
  recv(_, in, _)
  in[0..3] = n
=>
  send(_, out, _)
  out[0..3] = in[0..3] + 1
  n := out[0..3]
```

Facts: {in = &recval, in[0..3] = n,
val = n + 1, recval = val,
out = &val}

Show: out[0..3] = in[0..3] + 1

rule verifies



Challenges

- Loops
  - Try to compute a fixpoint
  - Gives up after 75 iterations
- For indirect assignments, only derive facts if write within bounds
  - And kill facts about the array otherwise
  - ...but do **not** forget everything else
- Functions inlined
- C data modeled as byte arrays
- Assume everything initialized to 0

Implementation

- Approximately 6,000 lines of OCaml
  - Uses CIL (http://manju.cs.berkeley.edu/cil/) to parse C programs
  - And Darwin as a theorem prover (http://combination.cs.uiowa.edu/Darwin/)
- Pistachio also uses user-provided specifications of library functions
  - In the same rule-based notation

Experimental Framework

- We used Pistachio on two protocols:
  - – LSH implementation of SSH2 (0.1.3 – 2.0.1)
    - 87 rules initially
    - Added 9 more to target specific bugs
  - – OpenSSH (1.0p1 - 2.0.1)
    - Same specification as above
  - – RCP implementation in Cygwin (0.5.4 – 1.3.2)
    - 51 rules initially
    - Added 7 more to target specific bugs
- Rule development time – approx. 7 hours

Example SSH2 Rule

“It is STRONGLY RECOMMENDED that the ‘none’ authentication method not be supported.”

```
recv(_, in, _ )
in[0] = SSH_MSG_USERAUTH_REQUEST
isOpen[in[1..4]] = 1
in[21..25] = “none”
=>
send(_, out, _ )
out[0] = SSH_MSG_USERAUTH_FAILURE
```

If we get an auth request

For the *none* method

Then send failure

Example Bug

```
1.  fmsgrecv(clisock, SSH2_MSG_SIZE);
2.  if(!parse_message(MSGTYPE_USERAUTHREQ, inmsg, len(inmsg),
        &authreq))
3.     return;
   ...............
4.  if(authreq.method == USERAUTH_PKI) {
 ...............
5.  } else if (authreq.method == USERAUTH_PASSWD) {
 ...............
6.  } else {
 ...............
7.  }
8.  sz = pack_message(MSGTYPE_REQSUCCESS, payload, outmsg,
        SSH2_MSG_SIZE);
9.  fmsgsend(clisock,outmsg,sz);
```

Message received

Handle PKI auth method

Handle passwd auth method

Oops – allow any other method

Send success; not supposed to send for *none* auth method

Another SSH2 Rule

“The server MUST respond to a TCP/IP forwarding request with the *wantreply* flag set to 1 and the port set to 0 with a request success message containing the forwarding port.”

```
 recv(in_sock, in, _ )
  in[0] = SSH_MSG_GLOBAL_REQUEST
  in[1..14] = “tcpip-forward”
  in[15] = 1
  in[(len(in) - 4)..(len(in) - 1)] = 0
=>
  send(out_sock, out, _ )
  in_sock = out_sock
  out[0] = SSH_MSG_REQUEST_SUCCESS
```

Given a forwarding request

with wantreply = 1

and the port = 0

send success

Example Buffer Overflow Bug

```
char laddr[17]; int lport;
 ...............
fmsgrecv(clisock,inmsg, SSH2_MSG_SIZE);
if(!parse_message(MSGTYPE_GLOBALREQ, inmsg,
                      len(inmsg), &globalreq))
  return;
 ...............
if(globalreq.msgtype==MSGSUBTYPE_TCPIPFORWARD)
 {
  strcpy(laddr,getstrfield(globalreq,payload,0));
  lport=getuint32field(globalreq,payload,1);
 ...............
  if(!create_forwarding(clisock,laddr,lport))
    return debug_error();
  if(globalreq.wantreply==1) && (lport == 0)) {
     payload.msgid=SSH_REQUEST_SUCCESS;
     payload.reason=lport;
     sz = pack_message(MSGTYPE_REQSUCCESS,
                      payload, outmsg, SSH2_MSG_SUZE);
     msgsend(clisock,outmsg,sz);
```

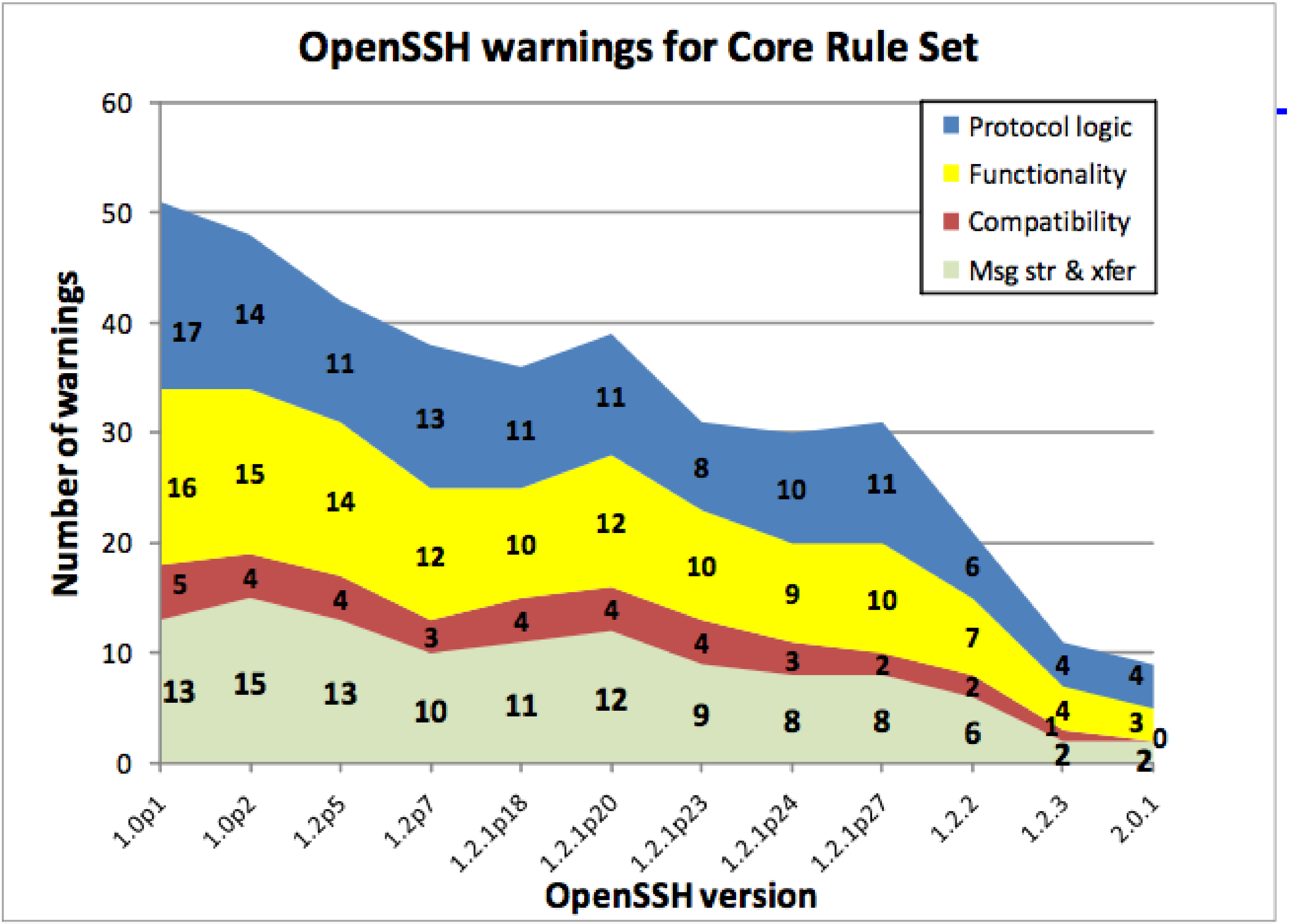
Watch this buffer

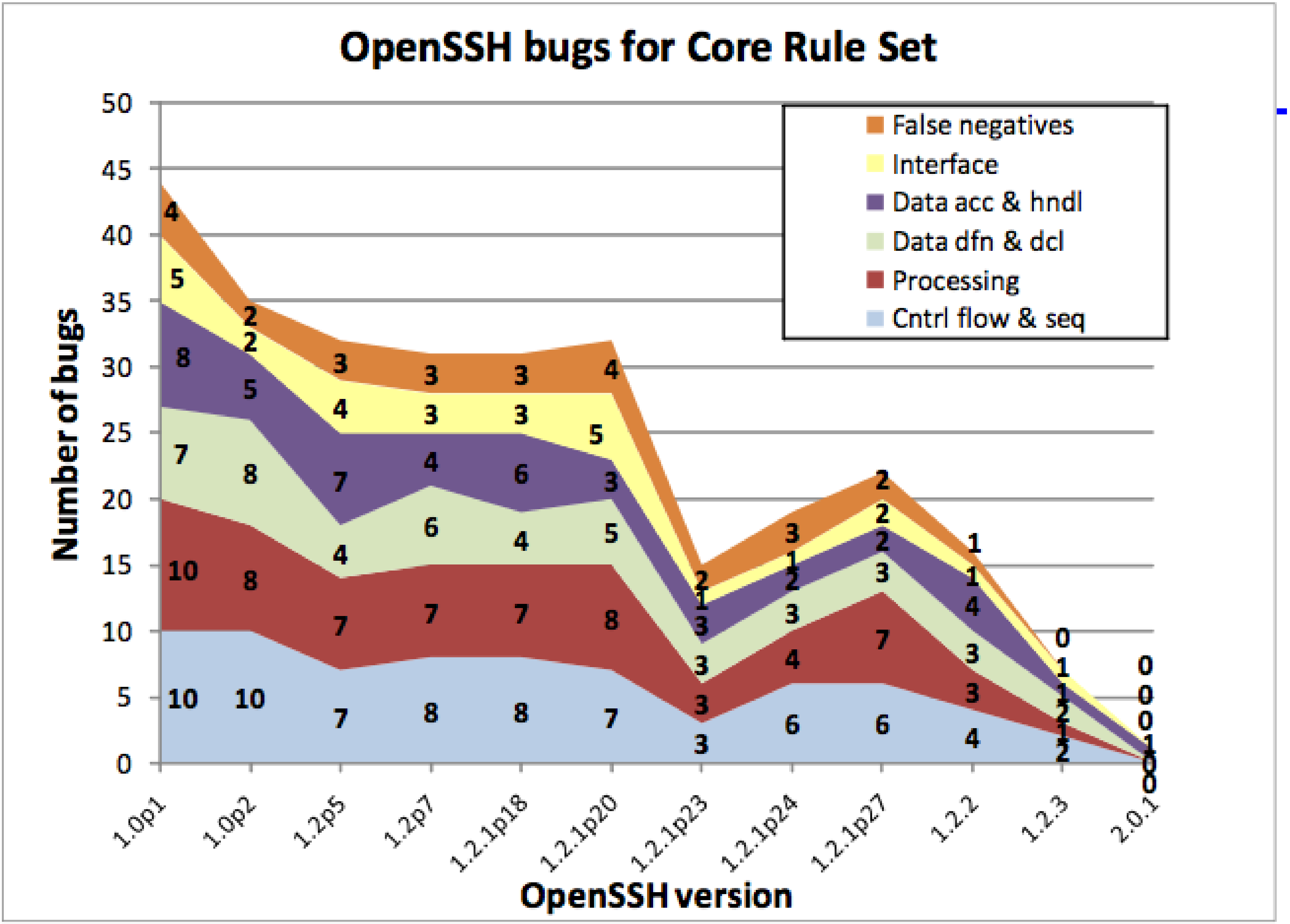
Receive message

If it’s a forwarding req

Uh-oh: strcpy to fixed buf
(getstrfield may return >17 bytes)

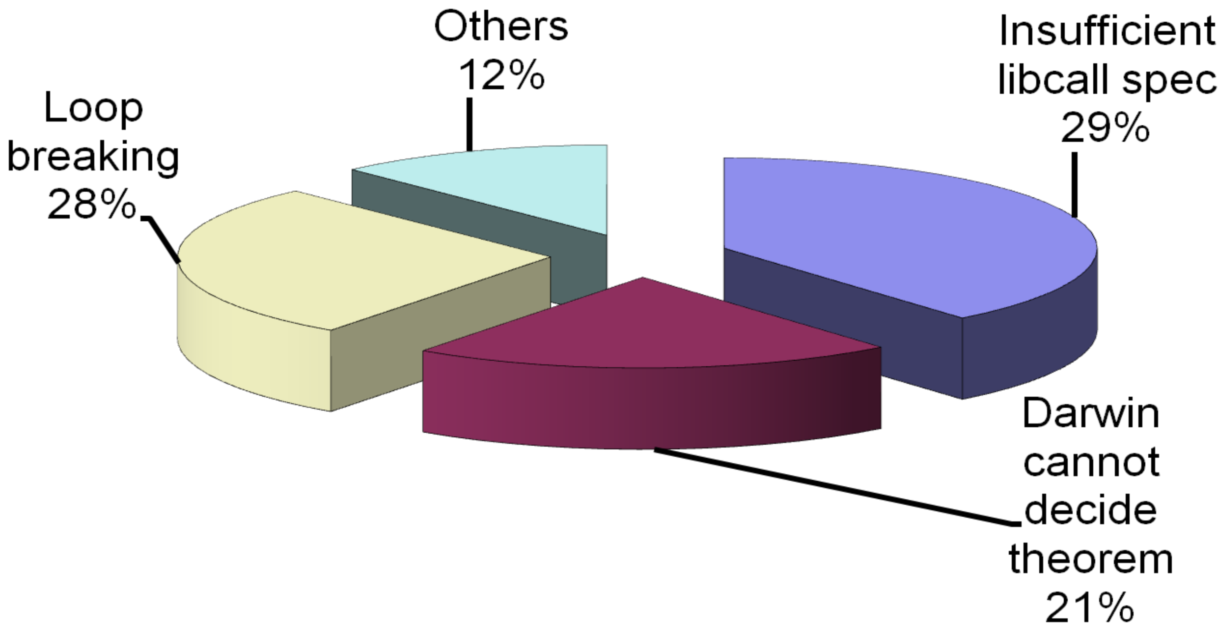
Pistachio thinks this may fail,
hence no msg sent


OpenSSH warnings for Core Rule Set
Number of warnings
60
50
40
30
20
10
0
Protocol logic
Functionality
Compatibility
Msg str & xfer
17
14
11
13
11
11
8
10
11
6
4
4
16
15
14
12
10
12
10
9
10
7
4
3
5
4
4
3
4
4
4
3
2
2
1
0
13
15
13
10
11
12
9
8
8
6
2
2
1.0p1
1.0p2
1.2p5
1.2p7
1.2.1p18
1.2.1p20
1.2.1p23
1.2.1p24
1.2.1p27
1.2.2
1.2.3
2.0.1
OpenSSH version



OpenSSH bugs for Core Rule Set

Causes of False Positives (LSH)



Discussion

- Network protocol implementations are a great target
  - Detailed specification available
  - Relatively small amount of code
  - Multiple implementations of the same protocol
- Better measurements of the utility of this analysis?
  - Able to find bugs that developers care about
  - How important were they?
- Could we eliminate these bugs in some other way?
  - A new language for network protocols?
  - What if used Pistachio during development?

Summary

- Rule-based specification closely related to RFCs and similar documents

- Initial experiments show Pistachio is a valuable tool
  - Very fast (under 1 minute)
  - Detects many security related errors
  - ...with low false positive and negative rates

http://www.cs.umd.edu/projects/PL