“Securing the Internet of Things”

# Specifying the DeepSpec Web Server


Lennart Beringer, Joachim Breitner, Olek Gierczak, Wolf Honore, Nicolas Koh, Yao Li, Yishuai Li, William Mansky, Benjamin C. Pierce, Stephanie Weirich, Li-Yao Xia, Steve Zdancewic


DeepSpec Workshop @ PLDI
June, 2018


Penn
University of Pennsylvania


deep spec server

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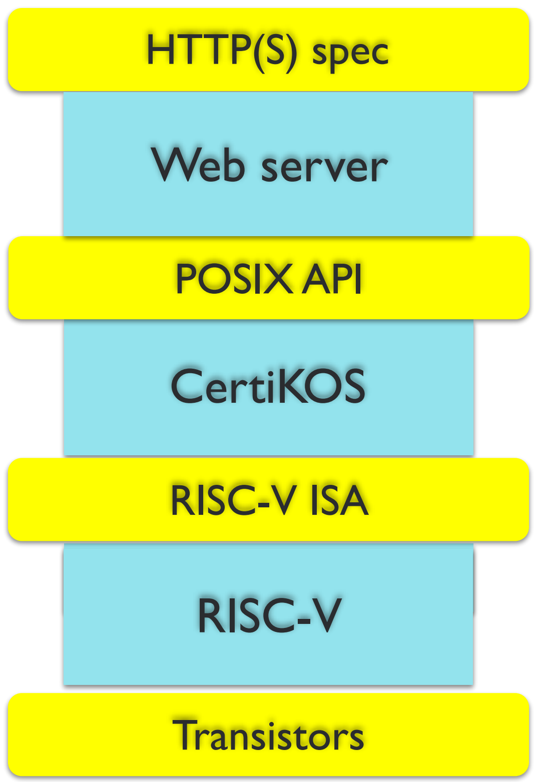
deep
spec
server

deep spec server =




Executable high-level specification of HTTP(S) protocols and web services

System call interface specification

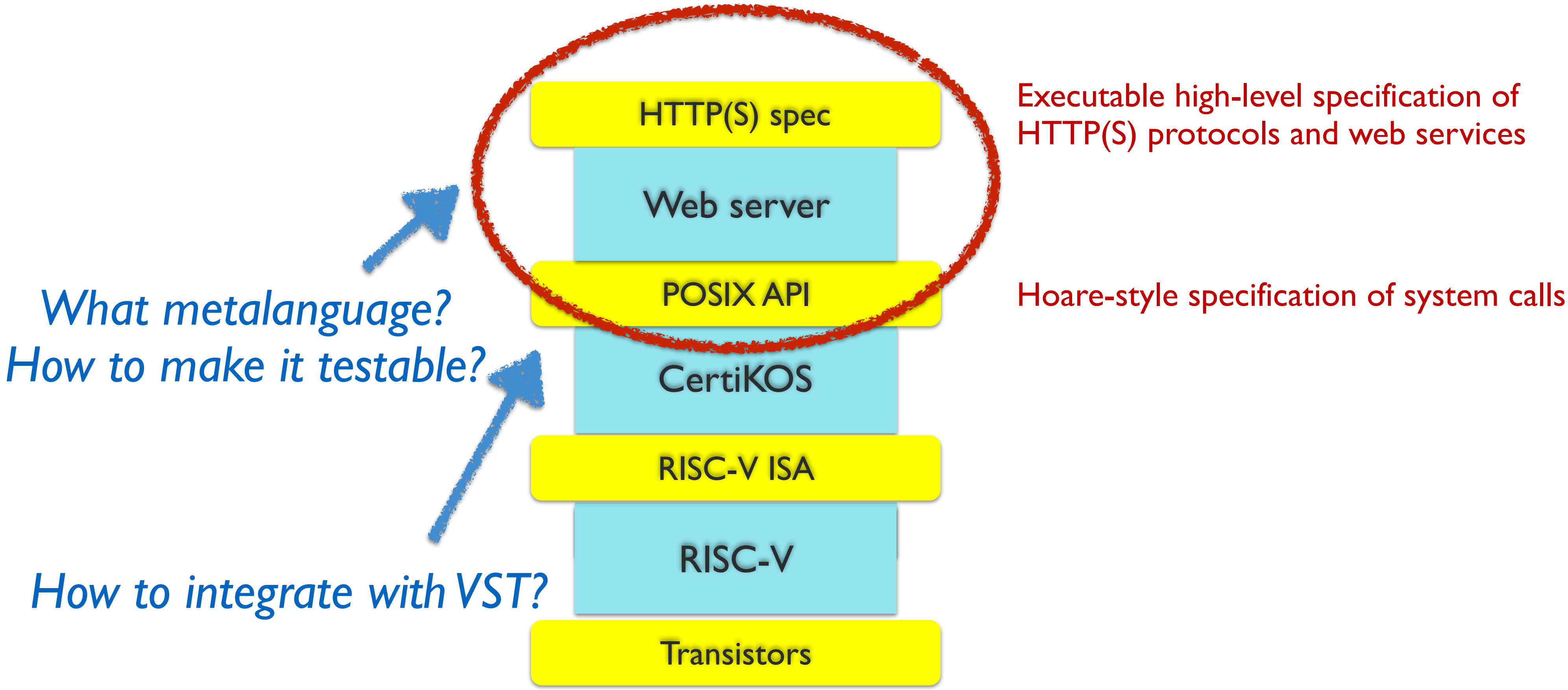
Instruction-set specification

RTL description of circuit behaviors

Goal: A “single QED” encompassing the entire software and hardware stack

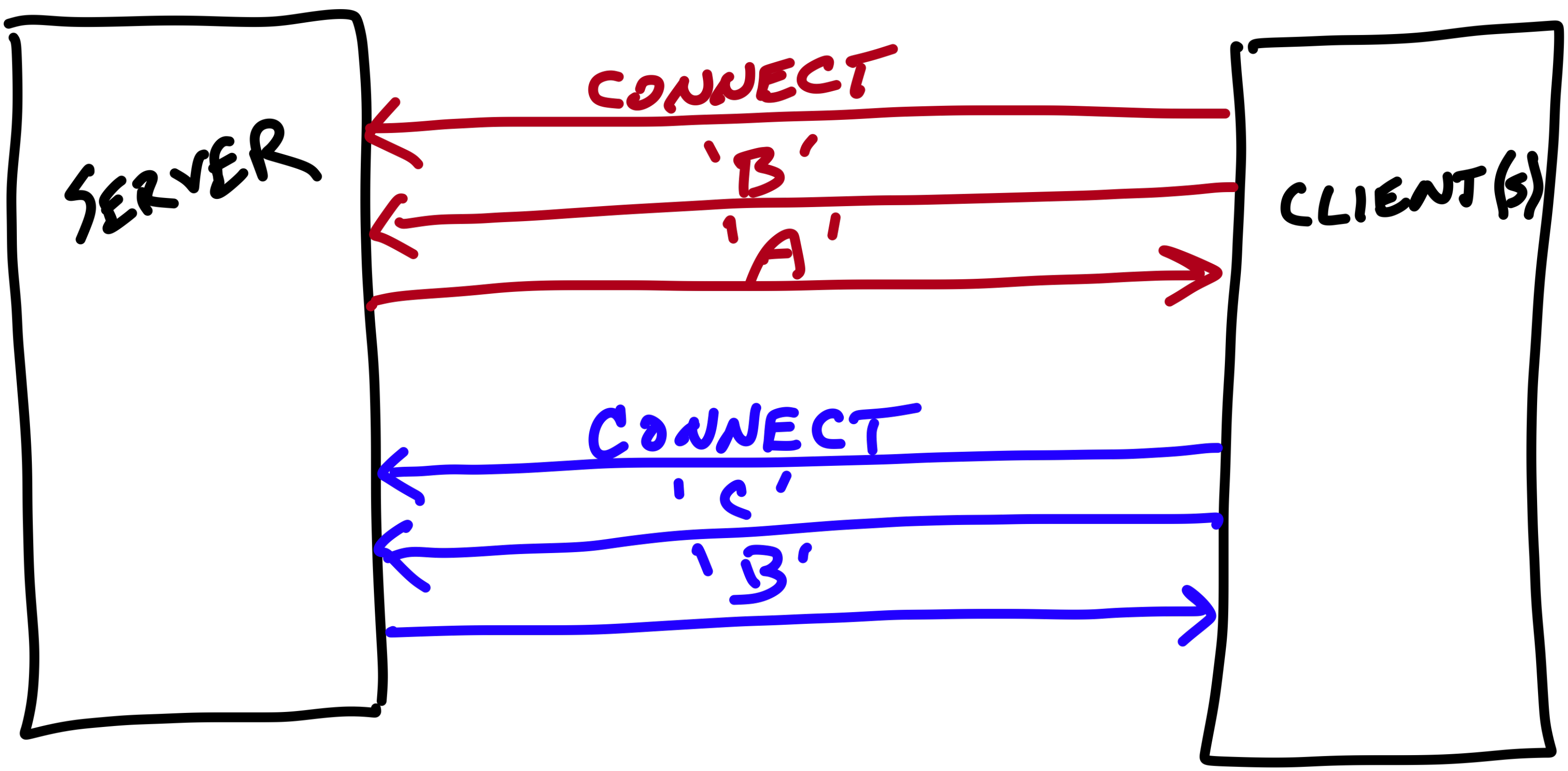
# The DeepSpec Web Server

- Based on popular GNU libmicrohttpd library
  - Clean separation between core HTTP-level functionality and the specifics of particular web services
- Aimed at embedded web servers (E.g. IoT device controllers)
- Current implementation (in C)
  - Parsing / printing of core HTTP formats; basic GET functionality
- Current specification (in Coq): ditto, plus
  - PUT functionality
  - ETag support for bandwidth conservation
- Later:
  - Broader coverage of HTTP standard documents
  - TLS authentication
  - Support for database-backed web services


HTTP(S) spec
Web server
POSIX API
CertiKOS
RISC-V ISA
RISC-V
Transistors
Executable high-level specification of HTTP(S) protocols and web services
Hoare-style specification of system calls
What metalanguage?
How to make it testable?
How to integrate with VST?

# Running Example

# A "Swap Server"



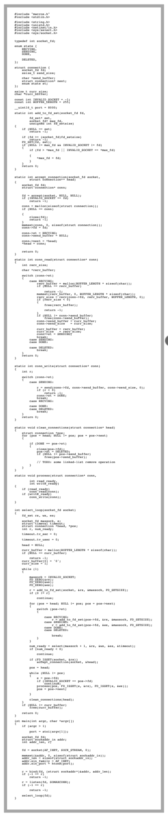
# Concrete swap server in C

```
#include "macros.h"
#include <stdlib.h>
#include <string.h>
#include <unistd.h>
#include <netinet/in.h>
#include <sys/select.h>
#include <sys/socket.h>

typedef int socket_fd;

enum state {
    RECVING,
    SENDING,
    DONE,
    DELETED,
};

struct connection {
    socket_fd fd;
    ssize_t send_size;
    char *send_buffer;
    struct connection* next;
```

# Concrete swap server in C

```c
[illegible]

typedef int socket_fd;

enum state {
    RECVING,
    SENDING,
    DONE,

    DELETED,
};

struct connection {
    socket_fd fd;
    ssize_t send_size;

    char *send_buffer;
    struct connection* next;
    enum state st;
};

ssize_t curr_size;
char *curr_buffer;

const int INVALID_SOCKET = -1;
const int BUFFER_LENGTH = 255;

__uint16_t port = 8000;

static int add_to_fd_set(socket_fd fd,

        fd_set* set,
        socket_fd* max_fd,
        unsigned int fd_setsize)
{
    if (NULL == set)
        return -1;

    if (fd >= (socket_fd)fd_setsize)
        return -1;
    FD_SET(fd, set);
    if (NULL != max_fd && INVALID_SOCKET != fd)
    {
        if (fd > *max_fd || INVALID_SOCKET == *max_fd)

        {
            *max_fd = fd;
        }
    }
    return 0;
}


static int accept_connection(socket_fd socket,
        struct connection** head)
{
    socket_fd fd;
    struct connection* conn;


    fd = accept(socket, NULL, NULL);
    if (INVALID_SOCKET == fd)
        return -1;

    conn = malloc(sizeof(struct connection));
    if (NULL == conn)

    {
        close(fd);
        return -1;
    }
    memset(conn, 0, sizeof(struct connection));
    conn->fd = fd;

    conn->st = RECVING;
    conn->send_buffer = NULL;

    conn->next = *head;
    *head = conn;


    return 0;
}

static int conn_read(struct connection* conn)
{
    int recv_size;

    char *recv_buffer;

    switch (conn->st)
    {
        case RECVING:
            recv_buffer = malloc(BUFFER_LENGTH * sizeof(char));
            if (NULL == recv_buffer)

                return -1;
            memset(recv_buffer, 0, BUFFER_LENGTH * sizeof(char));
            recv_size = recv(conn->fd, recv_buffer, BUFFER_LENGTH, 0);
            if (recv_size < 0)
            {
                free(recv_buffer);

                return -1;
            }
            if (NULL != conn->send_buffer)
                free(conn->send_buffer);
            conn->send_buffer = curr_buffer;
            conn->send_size   = curr_size;

            curr_buffer = recv_buffer;
            curr_size   = recv_size;
            conn->st = SENDING;
            break;
        case SENDING:
        case DONE:

        case DELETED:
            break;
    }
    return 0;
}


static int conn_write(struct connection* conn)
{
    int r;

    switch (conn->st)
    {
        case SENDING:

            r = send(conn->fd, conn->send_buffer, conn->send_size, 0);
            if (r < 0)
                return -1;
            conn->st = DONE;
            break;
        case RECVING:

        case DONE:
        case DELETED:
            break;
    }
    return 0;
}


static void clean_connections(struct connection* head)
{
    struct connection *pos;
    for (pos = head; NULL != pos; pos = pos->next)
    {

        if (DONE == pos->st)
        {
            close(pos->fd);
            pos->st = DELETED;
            if (NULL != pos->send_buffer)
                free(pos->send_buffer);

            // TODO: some linked-list remove operation
        }
    }
}

static void process(struct connection* conn,

        int read_ready,
        int write_ready)
{
    if (read_ready)
        conn_read(conn);
    if (write_ready)
        conn_write(conn);

}


int select_loop(socket_fd socket)
{
    fd_set rs, ws, es;

    socket_fd maxsock, s;
    struct timeval timeout;
    struct connection *head, *pos;
    int r, num_ready;

    timeout.tv_sec = 0;

    timeout.tv_usec = 0;

    head = NULL;

    curr_buffer = malloc(BUFFER_LENGTH * sizeof(char));
    if (NULL == curr_buffer)

        return -1;
    curr_buffer[0] = '0';
    curr_size = 1;

    while (1)
    {

        maxsock = INVALID_SOCKET;
        FD_ZERO(&rs);
        FD_ZERO(&ws);
        FD_ZERO(&es);

        r = add_to_fd_set(socket, &rs, &maxsock, FD_SETSIZE);
        if (0 != r)

            continue;

        for (pos = head; NULL != pos; pos = pos->next)
        {
            switch (pos->st)
            {

                case RECVING:
                    r = add_to_fd_set(pos->fd, &rs, &maxsock, FD_SETSIZE);
                case SENDING:
                    r = add_to_fd_set(pos->fd, &ws, &maxsock, FD_SETSIZE);
                case DONE:
                case DELETED:

                    break;
            }
        }

        num_ready = select(maxsock + 1, &rs, &ws, &es, &timeout);
        if (num_ready < 0)

            continue;

        if (FD_ISSET(socket, &rs))
            accept_connection(socket, &head);

        pos = head;

        while (NULL != pos)
        {
            s = pos->fd;
            if (INVALID_SOCKET == pos->fd)
                continue;
            process(pos, FD_ISSET(s, &rs), FD_ISSET(s, &ws));
            pos = pos->next;

        }

        clean_connections(head);
    }
    if (NULL != curr_buffer)
        free(curr_buffer);

    return 0;
}

int main(int argc, char *argv[])
{
    if (argc > 1)

        port = atoi(argv[1]);

    socket_fd fd;
    struct sockaddr_in addr;
    int addr_len, r;


    fd = socket(AF_INET, SOCK_STREAM, 0);

    memset(&addr, 0, sizeof(struct sockaddr_in));
    addr_len = sizeof(struct sockaddr_in);
    addr.sin_family = AF_INET;
    addr.sin_port = htons(port);


    r = bind(fd, (struct sockaddr*)&addr, addr_len);
    if (-1 == r)
        return -1;

    r = listen(fd, SOMAXCONN);
    if (-1 == r)

        return -1;

    select_loop(fd);
}
```

Concrete swap server in C



Verified Software Toolchain

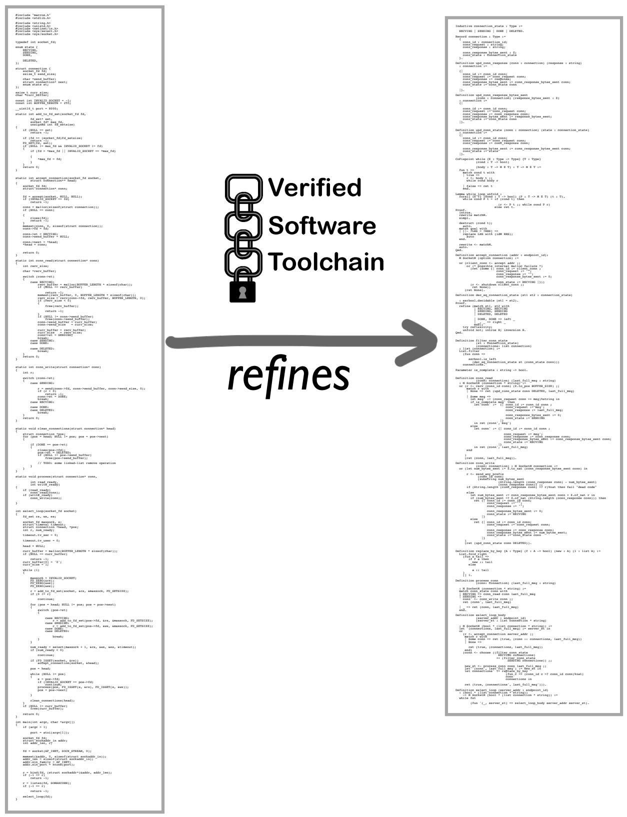
refines

Functional model in Gallina

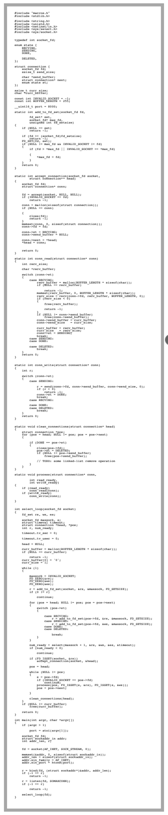
```
Inductive connection_state : Type :=
  RECVING | SENDING | DONE | DELETED.

Record connection : Type :=
  {
    conn_id : connection_id;
    conn_request : string;
    conn_response : string;
    conn_response_bytes_sent : Z;
    conn_state : connection_state
  }.

Definition upd_conn_response (conn : connection) (response : string)
  : connection :=
  {|
    conn_id := conn_id conn;
    conn_request := conn_request conn;
    conn_response := response;
    conn_response_bytes_sent := conn_response_bytes_sent conn;
    conn_state := conn_state conn
  |}.

Definition upd_conn_response_bytes_sent
           (conn : connection) (response_bytes_sent : Z)
  : connection :=
  {|
    conn_id := conn_id conn;
    conn_request := conn_request conn;
    conn_response := conn_response conn;
    conn_response_bytes_sent := response_bytes_sent;
    conn_state := conn_state conn
  |}.

Definition upd_conn_state (conn : connection) (state : connection_state)
```

Concrete swap server in C

Functional model in Gallina



Concrete swap server in C



Verified Software Toolchain

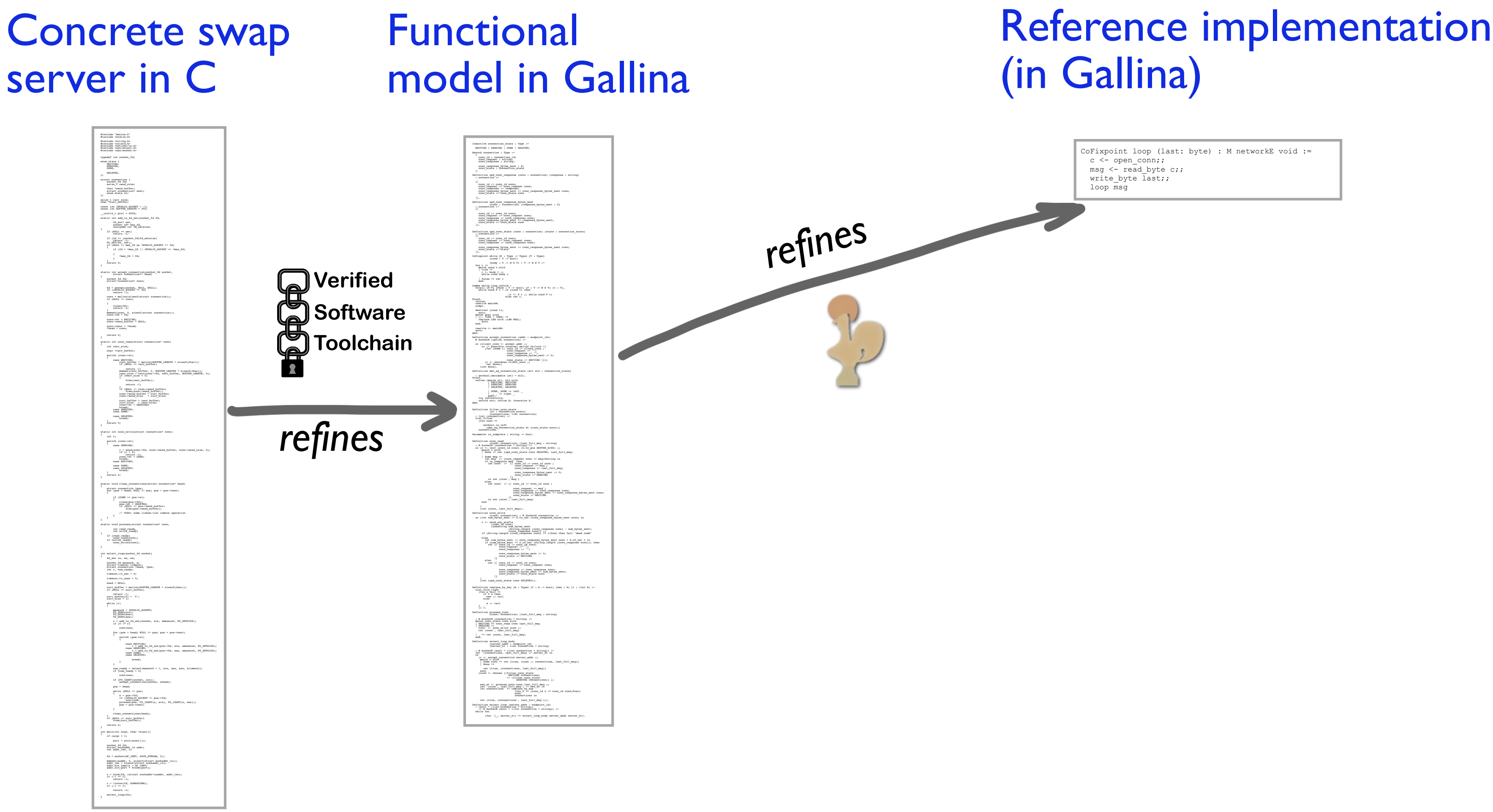
*refines*

Functional model in Gallina

*refines*

Reference implementation (in Gallina)

```
CoFixpoint loop (last: byte) : M
networkE void :=
  c <- open_conn;;
  msg <- read_byte c;;
  write_byte last;;
  loop msg
```


Concrete swap server in C
Functional model in Gallina
Reference implementation (in Gallina)
Verified Software Toolchain
refines
refines
CoFixpoint loop (last: byte) : M networkE void :=
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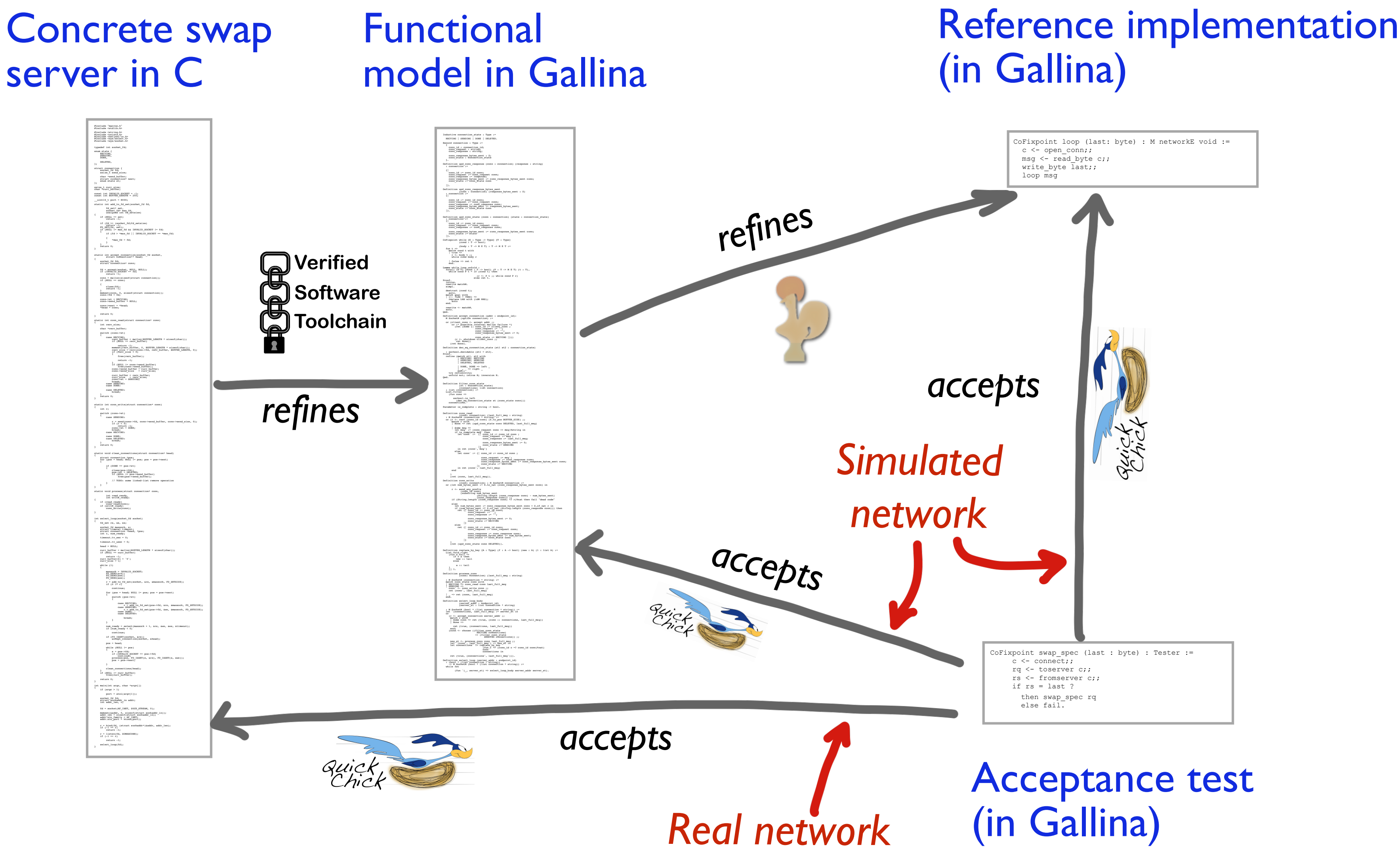
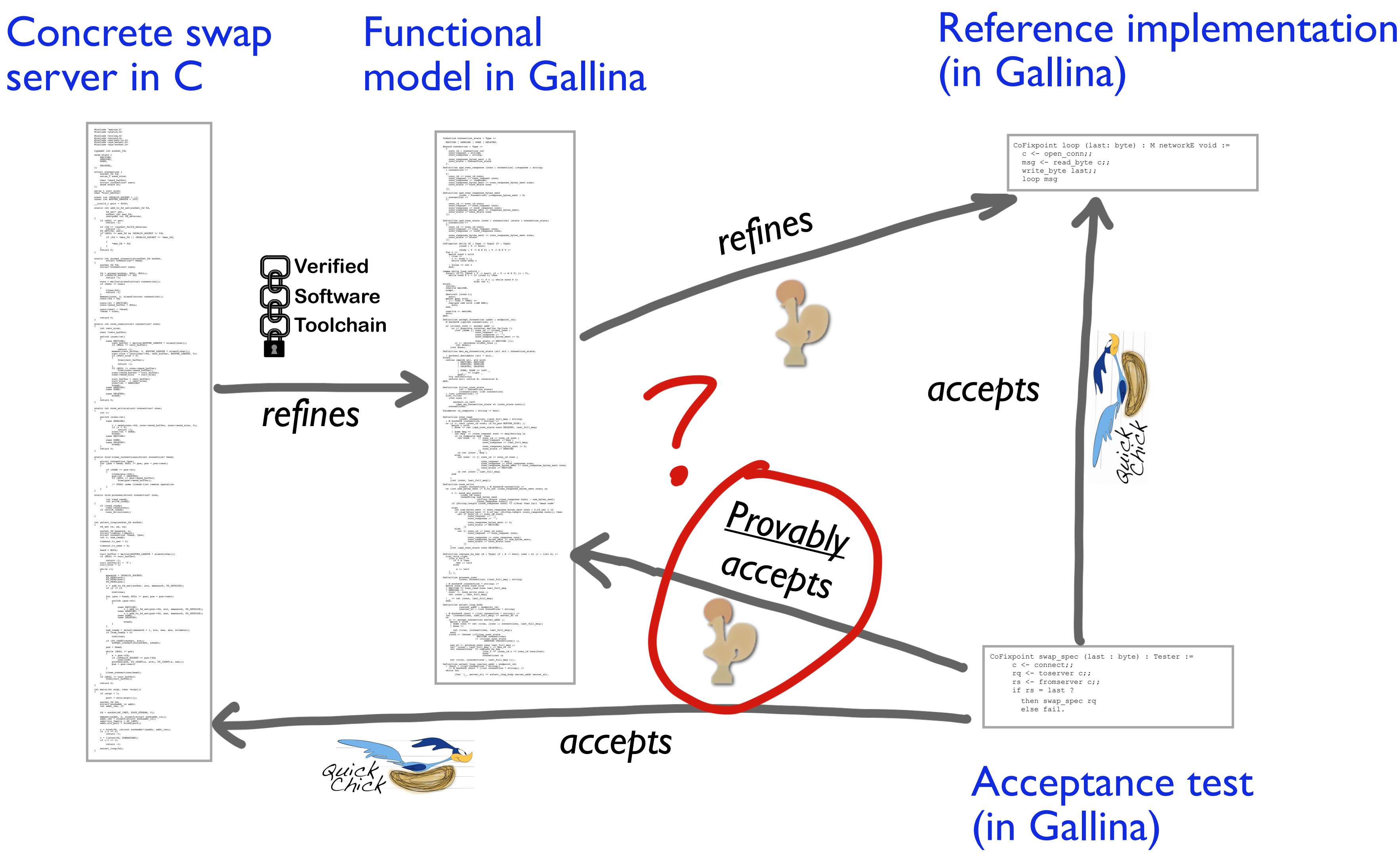
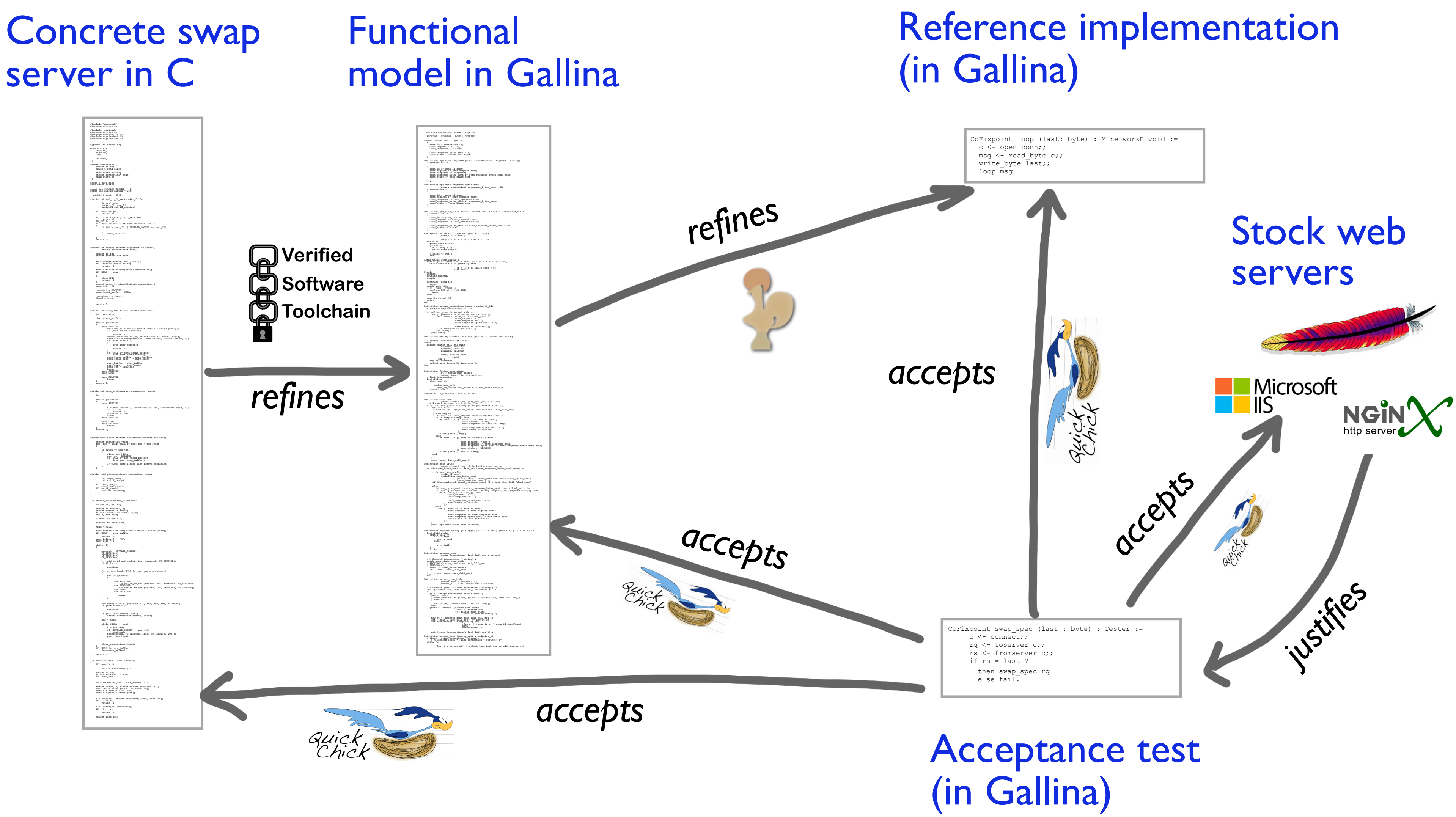

Concrete swap server in C
Functional model in Gallina
Reference implementation (in Gallina)
CoFixpoint loop (last: byte) : M networkE void :=
c <- open_conn;;
msg <- read_byte c;;
write_byte last;;
loop msg
Verified Software Toolchain
refines
refines
accepts
Simulated network
accepts
QuickChick
CoFixpoint swap_spec (last : byte) : Tester :=
c <- connect;;
rq <- toserver c;;
rs <- fromserver c;;
if rs = last ?
then swap_spec rq
else fail.
accepts
Real network
Acceptance test (in Gallina)


Concrete swap server in C
Functional model in Gallina
Reference implementation (in Gallina)
CoFixpoint loop (last: byte) : M networkE void :=
c <- open_conn;;
msg <- read_byte c;;
write_byte last;;
loop msg
Verified Software Toolchain
refines
refines
?
Provably accepts
accepts
accepts
QuickChick
QuickChick
CoFixpoint swap_spec (last : byte) : Tester :=
c <- connect;;
rq <- toserver c;;
rs <- fromserver c;;
if rs = last ?
then swap_spec rq
else fail.
Acceptance test (in Gallina)



Concrete swap server in C
Functional model in Gallina
Reference implementation (in Gallina)
CoFixpoint loop (last: byte) : M networkE void :=
c <- open_conn;;
msg <- read_byte c;;
write_byte last;;
loop msg
Verified Software Toolchain
refines
refines
accepts
Stock web servers
Microsoft IIS
NGINX http server
accepts
accepts
accepts
justifies
CoFixpoint swap_spec (last : byte) : Tester :=
c <- connect;;
rq <- toserver c;;
rs <- fromserver c;;
if rs = last ?
then swap_spec rq
else fail.
Quick Chick
Acceptance test (in Gallina)

# Early results: Testing stock web servers

I.e.,. The server said it was rejecting our PUT, but actually executed it!

- Apache
  - Nonstandard responses:
    - For GET requests that expect 200 OK, Apache sometimes clos… …ng the full response
    - For GET requests that expect 404 Not Found, Apache sometimes responds 403 Forbidden
  - Wrong behavior:
    1. Unconditional PUT, return 204 No Content
    2. Unconditional GET, return 200 OK with ETag
    3. Conditional If-Match PUT with ETag from 2, return 412 Precondition Failed
    4. Unconditional GET, return 200 OK with content from 3
- Nginx
  - One similar (but less serious) wrong behavior found so far

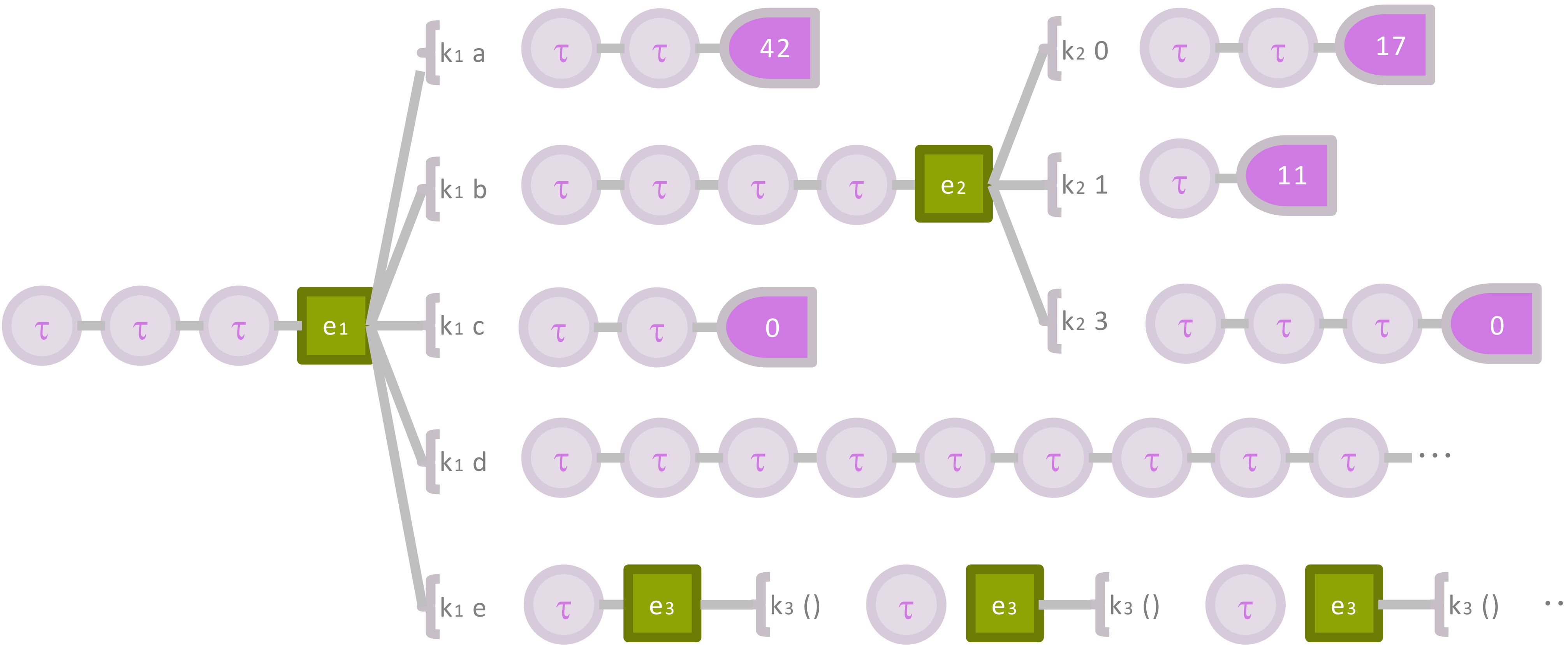
# A Common Metalanguage

# Too many metalanguages!

- Network-level HTTP spec
  - Functional program in Gallina
- Web server implementation
  - CompCert "observation traces"
- VST C verification tool
  - Hoare triples in separation logic
- CertiKOS
  - "Layer interfaces"

# Interaction Trees

- “Abstract syntax trees” for computations
- Nodes labeled with constructors drawn from some set of observable effects and branching corresponding to possible results of observations
- Can be given a variety of semantics by supplying different interpretations for the effects
- Effects can be varied to model different views of a computation
  - e.g., “OS view” vs “network view”


τ
τ
τ
e1
k1 a
τ
τ
42
k1 b
τ
τ
τ
τ
e2
k2 0
τ
τ
17
k2 1
τ
11
k2 3
τ
τ
τ
0
k1 c
τ
τ
0
k1 d
τ
τ
τ
τ
τ
τ
τ
τ
τ
...
k1 e
τ
e3
k3 ()
τ
e3
k3 ()
τ
e3
k3 ()
...

# Interaction Trees

```
CoInductive M (Event : Type -> Type) X :=
| Ret (x:X)
| Tau (k: M Event X).
| Vis {Y: Type} (e : Event Y) (k : Y -> M Event X)
```

An `M E X` is the denotation of a program as a possibly infinite (coinductive) tree, parameterized over a type `Event` of observable events where:

- leaves correspond to final results labeled with `X`,
- internal nodes node are either
  - internal events (labeled `Tau`), or
  - observable events (labeled `Vis`, with a child for every element of the event's result type `Y`).

# Network events

```
Inductive networkE : Type -> Type :=
  | OpenConn : networkE connection
  | ReadByte : connection -> networkE (option byte)
  | WriteByte : connection -> byte -> networkE unit.

Definition embed : forall {E X}, E X -> M E X :=
  fun E X e => Vis e (fun x => Ret x).

Definition open_conn : M networkE connection :=
  embed OpenConn.
Definition read_byte conn : M networkE (option byte) :=
  embed (ReadByte conn).
Definition write_byte conn b : M networkE unit :=
  embed (WriteByte conn b).
```

# Network events

```
Inductive networkE : Type -> Type :=
  | OpenConn : networkE connection
  | ReadByte : connection -> networkE (option byte)
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# Network events

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Definition open_conn : M networkE connection :=
  embed OpenConn.
Definition read_byte conn : M networkE (option byte) :=
  embed (ReadByte conn).
Definition write_byte conn b : M networkE unit :=
  embed (WriteByte conn b).
```

“Reference implementation” of the swap server as an interaction tree

```
CoFixpoint loop (last: byte) : M networkE void :=
  c <- open_conn;;
  msg <- read_byte c;;
  write_byte last;;
  loop msg
```

# Testing over the Network

# Where to observe?

# One view

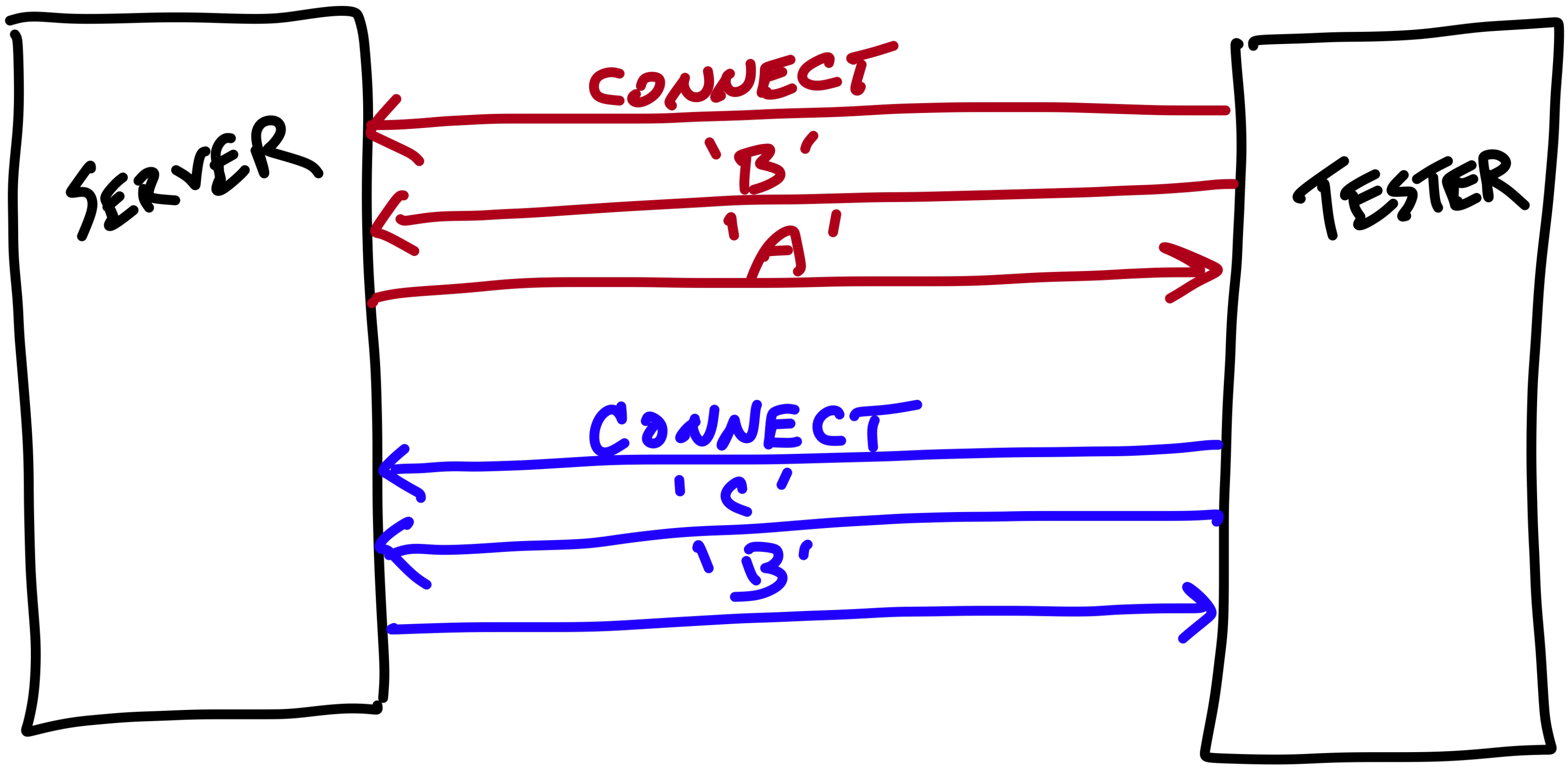
- A program interacts with the outside world via the operating system.
- The observations we can make of it are the OS calls it makes (together with their results)
- But what if we want to verify the whole stack?
  - program + OS + hardware??

# Another view

- A program running on an OS running on some hardware interacts with the outside world via its I/O ports
- Put a probe on the ethernet cable coming out of the box
- But what's *actually* on the wire?
  - electrical or optical waves?
  - raw seething bits?
  - IP packets?
  - TCP packets?
  - (HTTP messages?)

## Yet another view

- Put some client machines on the other end of the wire
- On each, run a browser on top of a standards-compliant protocol stack
- Put a probe into the internals of each client, at the level where TCP connections are decoded into bytestreams
- Specify OS primitives like send and recv in terms of the effects they have on externally visible bytestreams (`networkE` events)


SERVER
TESTER
CONNECT
'B'
'A'
CONNECT
'C'
'B'

```
Inductive testingE : Type -> Type :=
| Connect : testingE connection
| ToServer : connection -> testingE byte
| FromServer : connection -> testingE byte
| Fail : testingE void.

Definition Tester := M testingE void.


Definition connect : M testingE connection :=
  embed Connect.
Definition toserver c : M testingE byte :=
  embed (ToServer c).
Definition fromserver c : M testingE byte :=
  embed (FromServer c).
Definition fail {X} : M testingE X :=
  Vis Fail (fun v : void => match v with end).
```

```
Inductive testingE : Type -> Type :=
| Connect : testingE connection
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Definition toserver c : M testingE byte :=
  embed (ToServer c).
Definition fromserver c : M testingE byte :=
  embed (FromServer c).
Definition fail {X} : M testingE X :=
  Vis Fail (fun v : void => match v with end).
```
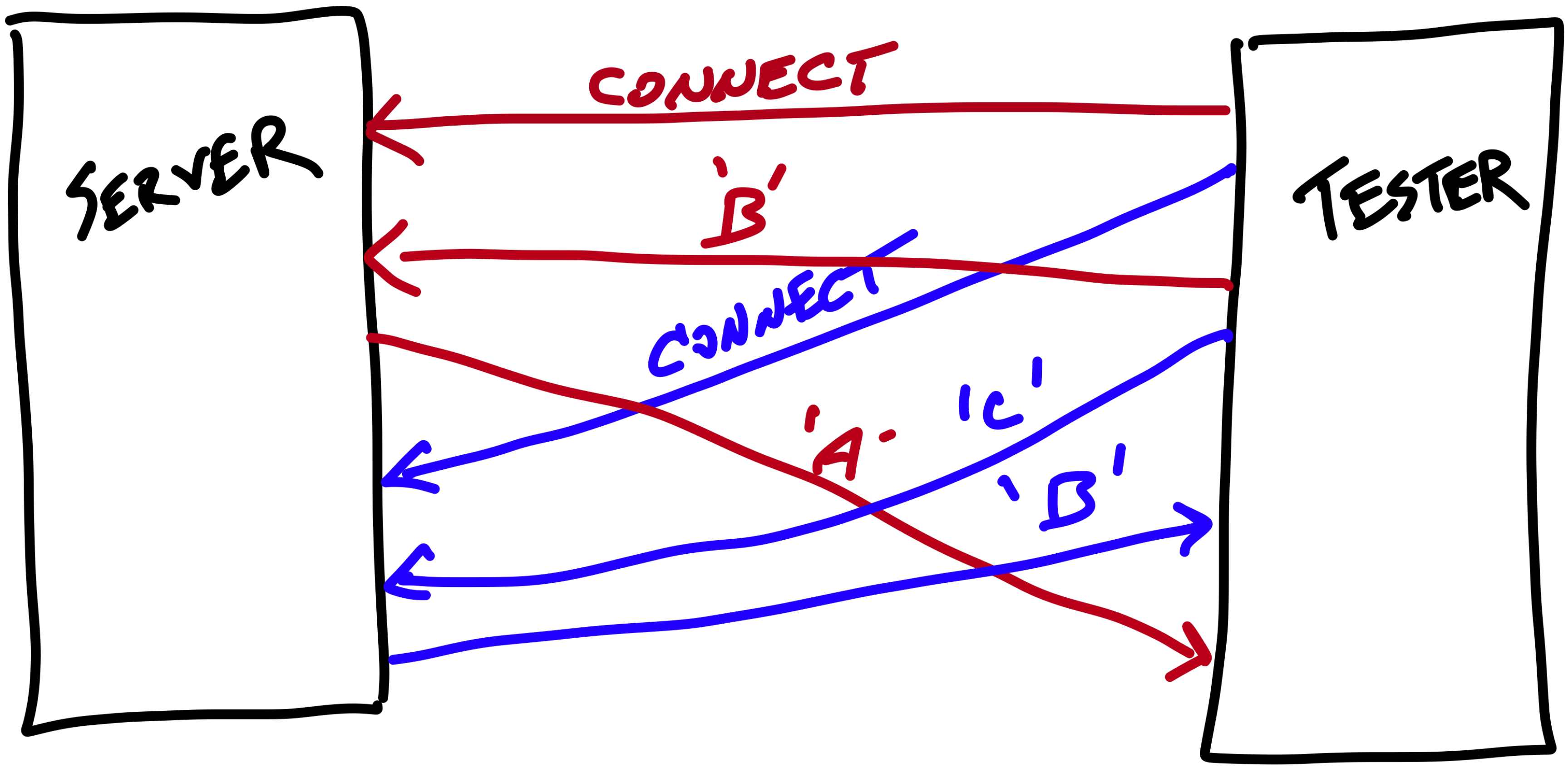
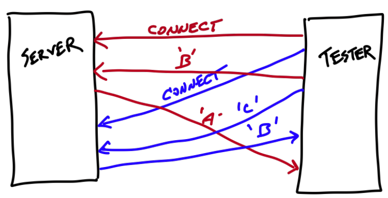

```
CoFixpoint swap_tester (last : byte) : Tester :=
     c <- connect;;
     rq <- toserver c;;
     rs <- fromserver c;;
     if rs = last ?
       then swap_tester rq
       else fail.
```

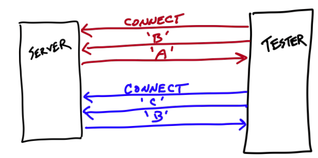
```
Inductive Event : Type :=
| ConnectE : connection -> Event
| ToServerE : connection -> byte -> Event
| FromServerE : connection -> byte -> Event.

Definition Trace := Trace.
```


SERVER
TESTER
CONNECT
'B'
CONNECT
'A'
'C'
'B'




observed trace
*(what the tester saw)*

`descramble`




*all server-side traces that could plausibly have generated the observed one*

```
Fixpoint check (ds: Trace) (t: Tester) : bool :=
  (* Check that trace ds is accepted by t… *)

Definition descramble (es: Trace) : list Trace :=
  (* Return all “server-side” traces that could
     have generated “client-side” observations es… *)

Definition acceptable (spec: Tester) (es: Trace) : bool :=
  existsb (fun ds => check ds spec) (descramble es).
```

```
acceptable (swap_spec 'A')
  [ConnectE 0;
   ToServerE 0 'B';
   FromServerE 0 'A';
   ConnectE 1;
   ToServerE 1 'C';
   FromServerE 1 'B']
= true

acceptable (swap_spec 'A')
  [ConnectE 0;
   ToServerE 0 'B';
   FromServerE 0 'A';
   ConnectE 1;
   ToServerE 1 'C';
   FromServerE 1 'A']
= false
```

```
more interestingly…

acceptable (swap_spec ‘A’)
  [ConnectE 0;
   ConnectE 1;
   ToServerE 0 ‘B’;
   ToServerE 1 ‘C’;
   FromServerE 1 ‘B’;
   FromServerE 0 ‘A’]
= true

acceptable (swap_spec ‘A’)
  [ConnectE 0;
   ConnectE 1;
   ToServerE 0 ‘B’;
   ToServerE 1 ‘C’;
   FromServerE 1 ‘A’;
   FromServerE 0 ‘A’]
= false
```

# Further Steps

- Test!  (Use QuickChick to generate test cases)
- Test faster!
  - Annotate Testers with hints describing how to generate requests to send to the server
  - Incrementalize / interleave testing and test-case generation
    - … so that we can see hints when we need them
    - … to manage combinatorial explosion of descrambling
- Test real servers (some more)!
- Prove!

# Interaction Trees and VST

# Interaction Trees in VST specifications

`{ ALLOWED(whole_server_itree) ; SOCKAPI(…) ; … }`

`C program`

`{ ALLOWED(null_itree) ; SOCKAPI(…) ; … }`

Hoare Triple

# Interaction Trees in VST specifications

*Internal state of OS*

```
{ ALLOWED(whole_server_itree) ; SOCKAPI(…) ; … }

                C program

    { ALLOWED(null_itree) ; SOCKAPI(…) ; … }
```

# Interaction Trees in VST specifications

*Remaining behavior*

{ **ALLOWED(whole_server_itree)** ; SOCKAPI(…) ; … }

C program

{ ALLOWED(null_itree) ; SOCKAPI(…) ; … }

# Interaction Trees in VST specifications

*Remaining behavior*

```
{ ALLOWED(whole_server_itree) ; SOCKAPI(…) ; … }

              C program

    { ALLOWED(null_itree) ; SOCKAPI(…) ; … }
```

*Remaining behavior*
*after this bit of C code runs*

## *VST Specification for Posix recv system call*

```
Definition recv_msg_spec (T : Type) :=
  DECLARE _recv_msg
  WITH t : SocketMonad T, k : option string -> SocketMonad T,
       client_conn : connection_id,
       st : SocketMap, (* A SocketMap maps file descriptors to socket states *)
       fd: sockfd,
       buf_ptr: val, alloc_len: Z, sh: share
  PRE [ 1 OF tint, 2 OF (tptr tuchar), 3 OF tuint, 4 OF tint ]
  PROP ( lookup_socket st fd = ConnectedSocket client_conn; writable_share sh ;
         trace_incl (msg <- recv client_conn (Z.to_pos alloc_len);; k msg) t
       )
    LOCAL (temp 1 (Vint (Int.repr (descriptor fd)));
           temp 2 buf_ptr;
           temp 3 (Vint (Int.repr alloc_len));
           temp 4 (Vint (Int.repr 0))
          )
    SEP ( SOCKAPI st; (* API memory contains some representation of st *)
            ALLOWED t;
            data_at_ sh (tarray tuchar alloc_len) buf_ptr
        )
```

*postcondition on next slide…*

```
POST [ tint ]
  EX result : unit + option string, (* result is either a failure, EOF, or received message *)
  EX st' : SocketMap,
  EX r : Z, EX contents: list val,
  PROP ( (0 <= r <= alloc_len) \/ r = -1; Zlength contents = alloc_len ;
          r > 0 ->
          (exists msg, result = inr (Some msg) /\
                  Zlength (val_of_string msg) = r /\
                  sublist 0 r contents = (val_of_string msg) /\
                  sublist r alloc_len contents =
                   list_repeat (Z.to_nat (alloc_len - r)) Vundef) /\ (st' = st) ;
          r = 0 -> (result = inr None /\ contents = list_repeat (Z.to_nat alloc_len) Vundef /\
                   st' = update_socket_state st fd OpenedSocket) ;
          r < 0 -> (result = inl tt /\
                   contents = list_repeat (Z.to_nat alloc_len) Vundef /\
                   st' = st)
       )
  LOCAL ( temp ret_temp (Vint (Int.repr r)) )
  SEP ( SOCKAPI st' ;
          ALLOWED ( match result with inl tt => t | inr msg_opt => k msg_opt end );
          data_at sh (tarray tuchar alloc_len) contents buf_ptr
      ).
```

## Status

- Swap server correctness proof nearly complete
  - Still experimenting with various ways of refactoring the specifications

## Next steps

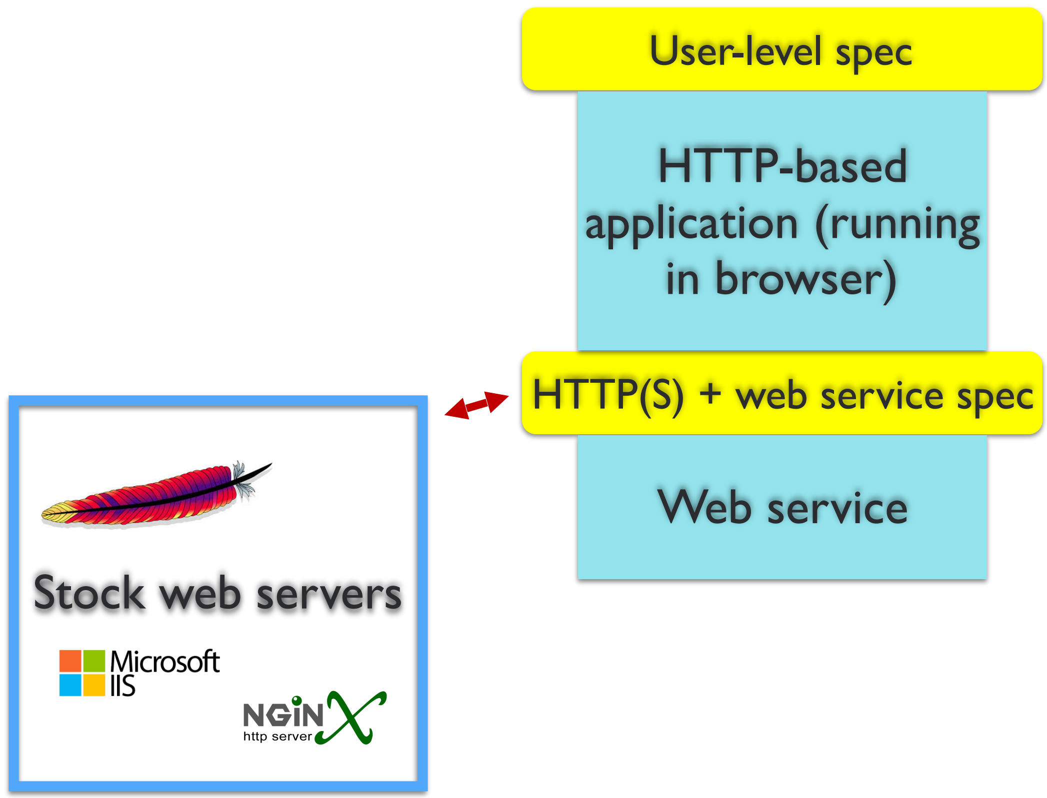
- Prove that CertiKOS implementation of POSIX socket API satisfies the axioms
- Scale proofs up to web server…

(More) questions?

# More slides

| Component | Approximate LOC |
| --- | --- |
| Common: axioms for socket API | 500 |
| C code for echo server | **140** |
| Interaction tree for echo server | 100 |
| Hoare triples for functions in echo server | 200 |
| VST proofs of C-to-OS-level-spec | 400 |
| Coq proofs of OS-level-to-network-level | 1000-2000 ? |
| **Total** | **1500-2500ish** |
| C code for web server | **2880** |
| Interaction tree for web server | 2000? |
| Hoare triples for web server | 4000? |
| VST proofs of C-to-OS-level-spec | 8000? |
| Coq proofs of OS-level-to-network-level | 20-40k? |
| **Total** | **30-50k ???** |

# Exercising the HTTP specification from both sides


User-level spec
HTTP-based application (running in browser)
HTTP(S) + web service spec
Web service
Stock web servers
Microsoft IIS
NGINX
http server

# Questions?