Verifying Authentication Properties of C Protocol Code Using VCC

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Verifying Security Code

- Assume a security API specification.
- Implementing this API concretely may introduce bugs:
  - Wrong interpretation by the programmer.
  - Bugs that are lower-level than the specification's abstraction.
- Verifying implementations addresses that issue.
  - fs2pv (CSF'06), Elyjah/Hajyle (ARSPA-WITS'08), F7 (CSF'08,POPL'10)
- But this verification should be done on programming languages that are used to write security code.
- We will focus on security protocol code written in C.

Verifying C Protocol Code

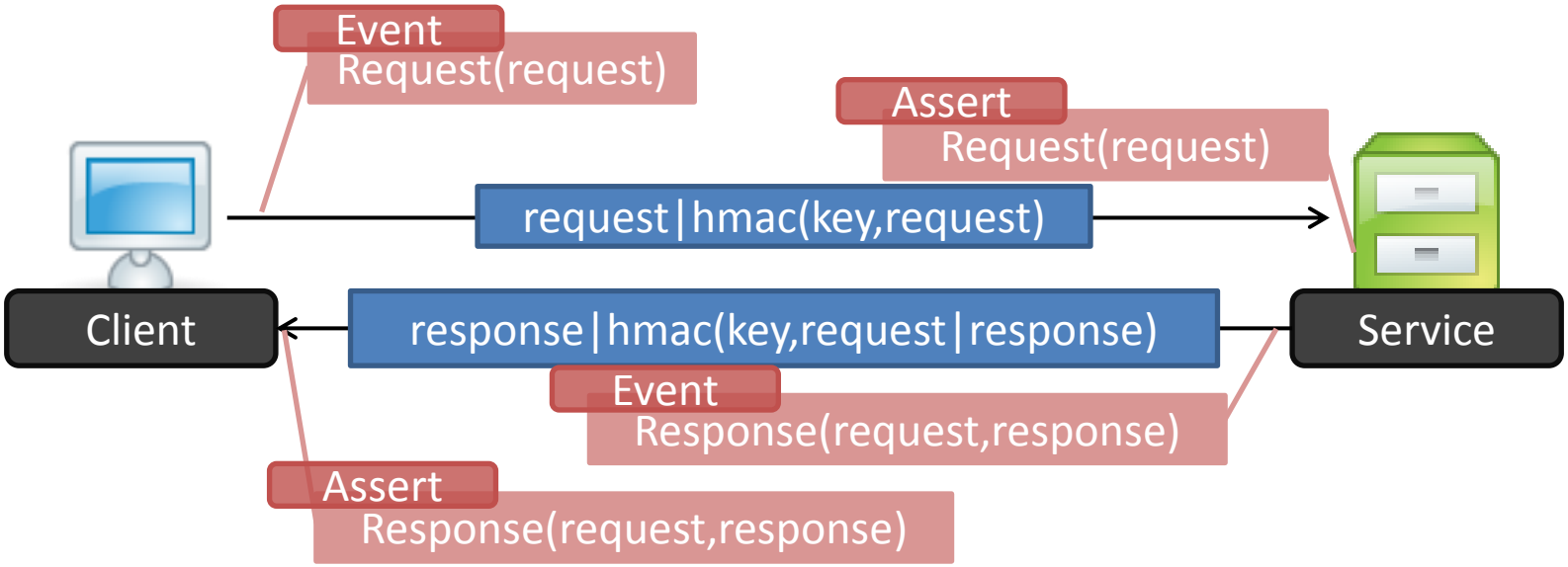
- C is used for performance, and in embedded systems.
- Fewer efforts on analysing C code:
  - Csur (VMCAI'05): trusted annotations, secrecy properties,
  - Aspier (CSF'09): trusted semantic description of subroutines, bounded settings, scalability issues,
  - Pistachio (USENIX'06): conformance verification only.
- We aim at verifying large security-critical projects in C.
  - Without too much manual work.
  - Without trusting user provided annotations.
- Our initial goal is to prove Dolev-Yao security, but we intend to later apply computational soundness results.

Our Method

- Using a general purpose verifier (VCC):
  - Bigger subset of the C language
  - Annotations are not trusted
  - Modular approach to verification
- Defining a Dolev-Yao attacker in the context of C programs.
  - Encoding the protocol state in the program state.
  - Encoding the attacker's capabilities as invariants.

Our running example:

Authenticated RPC



AN ATTACKER MODEL FOR C PROGRAMS

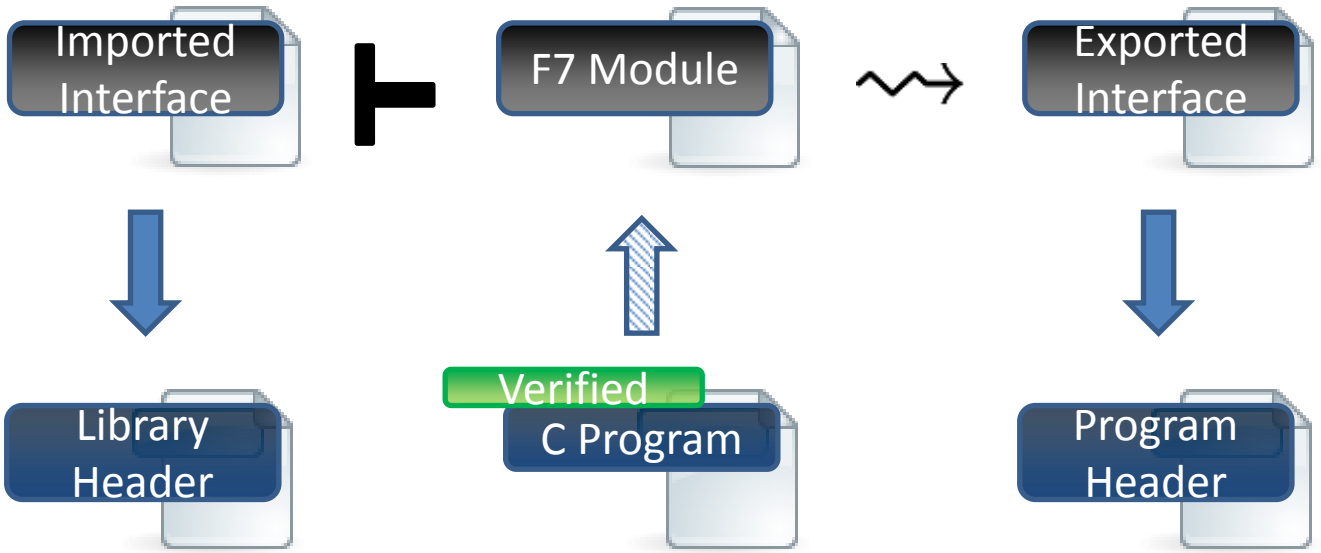
Attacker Model for C Programs

- We want to define a Dolev-Yao attacker model on C programs.
- F7 (POPL'10) defines a Dolev-Yao attacker model and a notion of security for the F# dialect of ML.
- Using the existing framework seems easier than defining an attacker directly on C.
- We could also benefit from future extensions to computational security.

Attacker Model for F7 Programs

- A type-checked F7 program forms a *refined module*, with imported (I_I) and exported (I_E) interfaces
- Result (POPL'10): In a refined module, if $I_I = \emptyset$, there is no type-safe way to use interface I_E that makes any of the module's assertions fail

Verified C Programs as Refined Modules



The VCC Assumption

If a C program P implements a header $h\ [\![I_E]\!]$ using a library $h\ [\![I_I]\!]$, then there exists an F7 module $\underline{P}$ such that $I_I \vdash \underline{P} \rightsquigarrow I_E$ (hence, no type-safe program using I_E can make any of the assertions in $\underline{P}$ fail).

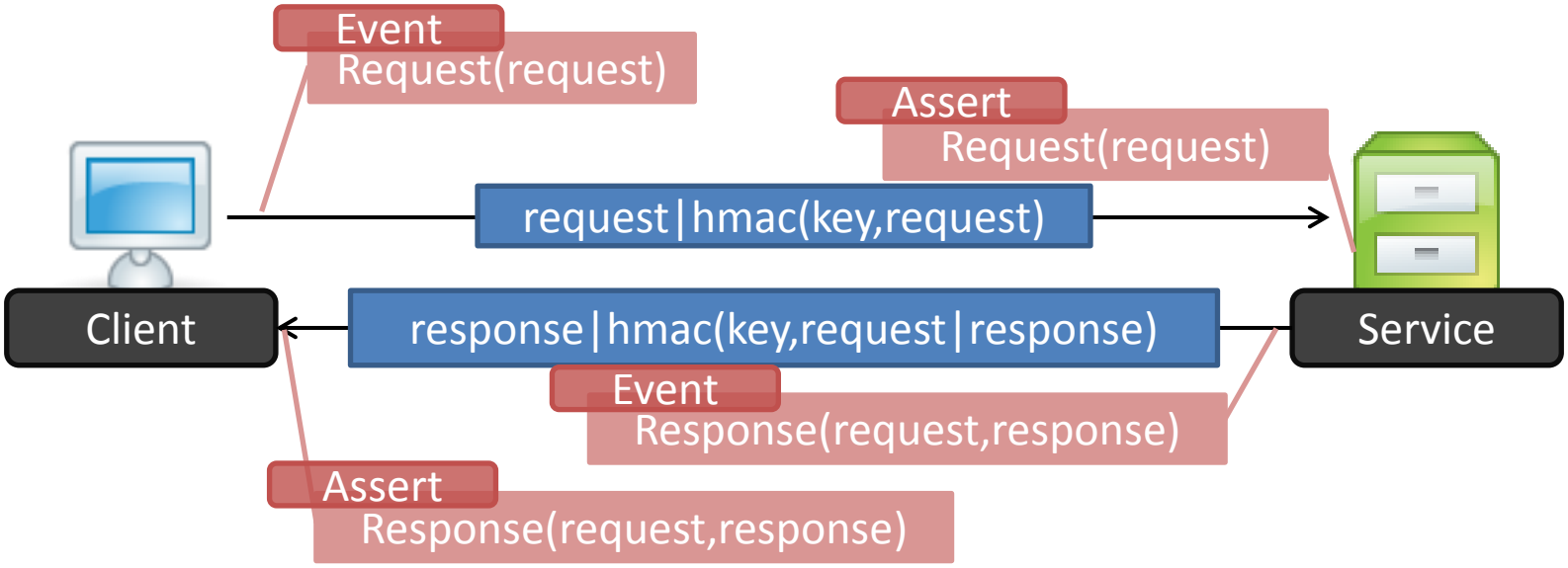
Attacker Model For C Programs

- If a C program is verified to implement an exported header using an imported header, we assume an equivalent F7 refined module.
- An attacker is a well-typed F7 program that uses the exported interface.
- We use results from F7 (composition, security of refined modules…) to prove security of the verified C program.

Case Study:

A VERIFIED C IMPLEMENTATION OF AUTHENTICATED RPC

Authenticated RPC
A Reminder



Imported Libraries

- Primitives for network, byte array and cryptographic operations.
- Event predicate declarations.
- Inductive predicate definitions.
- For simplicity, we also include some protocol-specific functions.

Imported Interface

F7 function declaration

```
val hmacsha1:
   k:bytes →
   b:bytes {Bytes(b)
           ∧ ((MKey(k) ∧  MACSays(k,b))
              ∨ (Pub(k) ∧ Pub(b)))} →
   h:bytes {Bytes(h)
           ∧ IsMAC(h,k,b)}
```

VCC function contract

```
term hmacsha1_RCF(term k, term b)
  ensures(result != 0)
  requires(Bytes(b))
  requires((MKey(k) && MACSays(k,b))
              || (Pub(k) && Pub(b)))
  ensures(Bytes(result) && IsMAC(result,k,b));
```

Exported Interface

- The imported libraries
- The client role

```
val client:
  a:bytes {String(a) ∧ Pub(a)} →
  b:bytes {String(b) ∧ Pub(b)} →
  k:bytes {Mkey(k) ∧ KeyAB(a,b,k)} →
  s:bytes {String(s) ∧ Pub(s)} →
  unit
```

```
void client(term a, term b, term k, term s)
requires(String(a) && Pub(a))
requires(String(b) && Pub(b))
requires(Mkey(k) && log->KeyAB[k][a][b])
requires(String(s) && Pub(s))
ensures(Stable(log));
```

- The server role

```
val server:
  a:bytes {String(a) ∧ Pub(a)} →
  b:bytes {String(b) ∧ Pub(b)} →
  k:bytes {Mkey(k) ∧ KeyAB(a,b,k)} →
  unit
```

```
void server(term a, term b, term k)
requires(String(a) && Pub(a))
requires(String(b) && Pub(b))
requires(Mkey(k) && log->KeyAB[k][a][b])
ensures(Stable(log));
```

Implementation

- To simplify memory-safety, we wrap byte arrays.

```
struct {
  unsigned char *ptr;
  unsigned long len;} bytes;
```

- We use ghost fields to specify their usage.

```
struct {
  unsigned char *ptr;
  unsigned long len;

  spec(mathint encoding;)
  invariant(keeps(as_array(ptr,len)))
  invariant(encoding == Encode(ptr,len))
} bytes;
```

- Encode() is a bijective encoding of byte arrays as integers, so we can talk about byte arrays as values.

Implementation

```
void client(bytes_c *a, bytes_c *b, bytes_c *k, bytes_c *s)
{
        bytes_c *req,*mac,*upay,*msg1;
        bytes_c *msg2,pload2,mac2,*t,*resp;
        int res;

        if ((req = malloc(sizeof(*req))) == NULL)
                return;
        if (request(s, req))
                return;

        if ((mac = malloc(sizeof(*mac))) == NULL)
                return;
        if (hmacsha1(k, req, mac))
                return;
        free(req);

        if ((upay = malloc(sizeof(*upay))) == NULL)
                return;
        if (utf8(s, upay))
                return;

        if ((msg1 = malloc(sizeof(*msg1))) == NULL)
                return;
        if (concat(upay, mac, msg1))
                return;
        free(upay);
        free(mac);

        send(msg1);
        free(msg1);

        if ((msg2 = malloc(sizeof(*msg2))) == NULL)
                return;
        if (recv(msg2))
                return;

        if (iconcat(msg2, &pload2, &mac2))
                return;
        free(msg2);

        if ((t = malloc(sizeof(*t))) == NULL)
                return;
        if (iutf8(&pload2, t))
                return;

        if ((resp = malloc(sizeof(*resp)) == NULL)
                return;
        if (response(s, t, resp))
                return;
        free(t);
        free(s);

        if (!hmacsha1Verify(k, resp, &mac2))
                return;
        free(resp);
}
```

Hybrid Wrappers

- Two goals:
  - Provide a concrete interface for realistic C code
  - Ensure consistency between the VCC axioms and our cryptographic definitions
- They are wrappers around both the concrete functions (e.g. OpenSSL crypto library) and the symbolic functions imported from RCF.
- Wrappers are verified so that:
  - The concrete part does not introduce run-time errors
  - The symbolic part follows the cryptographic invariants

Hybrid Representation

- The encoding function is a mapping from arrays of bytes to mathematical integers
- The F7 functions manipulate Dolev-Yao terms
- We keep the models in lock-step using two partial maps:

```
term B2T[bytes];
bytes T2B[term];

invariant(forall(bytes b; B2T[b] != 0 ==> T2B[B2T[b]] == b)
invariant(forall(term t; T2B[t] != 0 ==> B2T[T2B[t]] == t)
```

Constructing a refined module

- What we have:
  - A refined module $(\emptyset, Lib, \mathbf{Lib})$, where $\mathbf{Lib}$ contains network and cryptographic functions, the predicate definitions, and the *request*, *response* and *service* functions (POPL'10).
  - Via the VCC assumption, a refined module $(\mathbf{Lib}, \underline{P}, \mathbf{RPC}^{-})$, where
    $\mathbf{RPC}^{-} = \mathbf{Lib}$; **val** client: …; **val** server:…

Constructing a refined module

- We can write, in F7, a wrapper function:

```
let setup (a:bytes {String(a)}) (b:bytes {String(b)}) =
    let k = mkKeyAB a b in
    (fun s -> client a b k s),
    (fun _ -> server a b k),
    (fun _ -> assume(Bad(a)); k),
    (fun _ -> assume(Bad(b)); k)
```

- And by composition, we can build a refined module $(\emptyset, M, (I_L, I_R))$, where (I_L, I_R) is the attacker interface defined in (POPL'10), and provides the attacker with control over the network and the principals (through the setup function).

Summary

- We define a Dolev-Yao attacker model for C programs and define the corresponding notion of security.
- We verify that a program is secure under certain assumptions:
  - The VCC assumption.
  - The assumption that cryptographic primitives fail instead of generating colliding byte arrays.

Summary – Case Study

- The RPC protocol roles (~60 LoC) are verified in about 3 minutes each.
- Necessary annotations:
  - Pre-conditions on the protocol roles (memory-safety + translated from F7): ~10 lines per role.
  - Library contracts (memory-safety + translated from F7): ~10 lines per function prototype.
  - Hybrid wrappers (20-50 lines per primitive depending on the library).
  - Some hints to the prover: < 10 lines per role, depending on memory behaviour.
- A lot of the annotations are memory-safety related.
- Some hybrid wrappers can be a lot of trouble (concatenation).

Future Work

- Weaken our assumptions.
- Compare this approach with more direct encodings of the attacker in VCC:
  - Performance (e.g. no inductive predicates).
  - Simplicity of the security result.
- Adapt to a computationally sound model:
  - Eliminate the hybrid wrappers and functional idioms.
  - Get computational guarantees.
- Apply to externally written code:
  - Protocols (*e.g.* PolarSSL).
  - Security API implementations? Suggestions are welcome.