User-Guided Verification of Security Protocols via Sound Animation

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Outline

Formal verification of security protocols

Successful applications

Authentication (5G AKA [BDH+18]), Handover (5G), Privacy, Access control, TLS (HTTPS), Payment (EMV[1]), and many more ...

[1] Basin et al. Tamarin: Verification of Large-Scale, Real World, Cryptographic Protocols. IEEE Security and Privacy Magazine (2022)

Formal verification of security protocols

Benefits

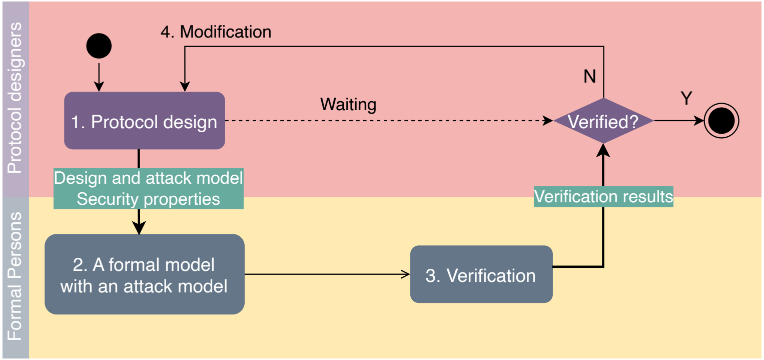
- Discovery of unknown vulnerabilities: Needham-Schroeder PKP [Low95], 5G AKA
- Identification of missing or weak assumptions: 5G AKA and handover
- Proposal of fixes or improvements to protocols: NSPK and 5G AKA
- Guarantee of correctness (EMV)

Formal verification of security protocols

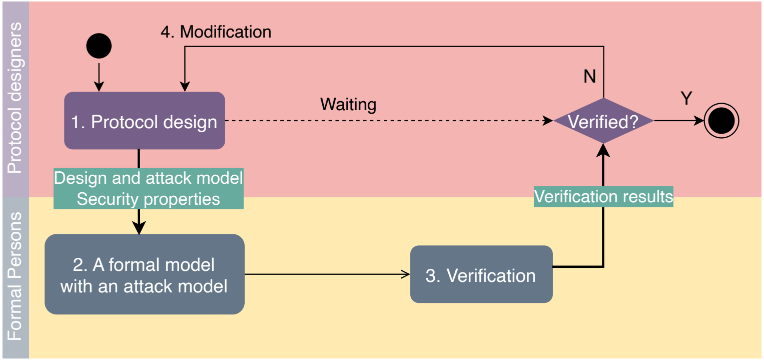
Notations and tools

- Process algebras: CSP (FDR) and Applied Pi Calculus (ProVerif)
- Inductive sets: Isabelle
- State-based: TLA^{+}-based AVISPA
- LTS and (multi-sets) rewriting rules: Maude-NPA, Tamarin-prover
- Model checking and theorem proving

Current practice and problems



Current practice and problems



Problems:

- Not accessible to designers
- Non-iterative, or slow-iteration

Accessible formal verification to engineers

Animation of a formal specification

- an executable computer program implemented in C/C++, Java, or Haskel etc.
- UI to interact with models for users
- Kazmierczak et al. [KWD98]: an animator for Z specifications
- Dutle et al. [DMNB15]: manually translate formally verified models to Java code
- Miller et al. [MBWN22]: an emulator (C++) to experiment with 5G AKE
- Boichut et al.'s SPAN [BGGH07]: an animation tool (OCaml and Tcl/Tk) for HLPSL, used in AVISPA.

Accessible formal verification to engineers

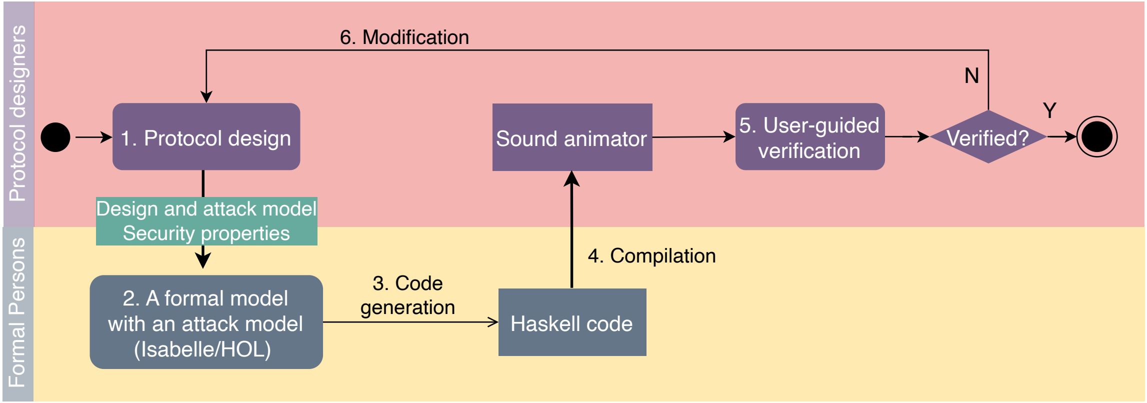
Problems: soundness is not guaranteed (implementations may have bugs), need efforts to develop code

Novel contributions

An interactive workflow supports

- automatically generated sound animators (Haskell),
- a lightweight and verified model checker: manual, automatic (exhaustive and random) exploration, reachability and feasibility checking
- a user-guided verification: automatic verification after manual exploration
- accessible to designers and fast iteration
- two case studies: Needham-Schroeder public key protocol (NSPK) and Diffie–Hellman key exchange protocol (DH)

Workflow to support user-guided verification



Interaction Trees[1] in Isabelle/HOL

Coinductive trees, with potentially infinite breadth and depth, used to represent the ways a process communicates with its environment and evolves over time.

Executable denotational semantics[2], originally mechanised in Coq

Mechanisation in Isabelle/HOL[3]

```
codatatype ('e, 'r) itree =
  Ret 'r |                              - ‹ Terminate, returning a value ›
  Sil "('e, 'r) itree" |                            - ‹ Invisible event ›
  Vis "'e ⇸ ('e, 'r) itree"          - ‹ Visible events and continuations ›
```

[1] Xia et al. 2019. Interaction trees: representing recursive and impure programs in Coq. Proc. ACM Program. Lang. 4, POPL

[2] Xia, L.y.: Executable Denotational Semantics with Interaction Trees. PhD thesis, 2022

[3] Foster et al. Formally verified simulations of state-rich processes using interaction trees in Isabelle/HOL. CONCUR (2021)

ITree-based Communicating Sequential Processes (CSP)[1,2]

- Deterministic processes
- Stateful processes: $P \fatsemi Q$
- No nondeterministic operator
- Biased external choice and parallel composition (priority)
- Hide with priority
- Renaming with priority

[1] Foster et al. Formally verified simulations of state-rich processes using interaction trees in Isabelle/HOL. CONCUR (2021)

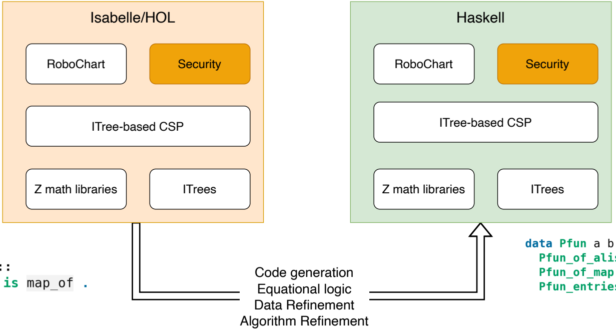
[2] Ye et al. Formally verified animation for RoboChart using interaction trees. JLAMP (2024)

Soundness: unbroken link from ITree-based CSP to Haskell

```
definition outp where
"outp c v =
  Vis
    (pfun_of_alist
      [(build⇘c⇙ v, Ret())])"
```

```
codatatype ('e, 'r) itree =
  Ret 'r |
  Sil "('e, 'r) itree" ("τ") |
  Vis "'e ⇸ ('e, 'r) itree"
```

```
lift_definition pfun_of_alist ::
  "('a × 'b) list ⇒ 'a ⇸ 'b" is map_of .
```




```
outp c v =
  Interaction_Trees.Vis
    (Interaction_Trees.Pfun_of_alist
      [(Prisms.prism_build c v,
        Interaction_Trees.Ret ())]);
```

```
data Itree a b =
  Ret b |
  Sil (Itree a b) |
  Vis (Pfun a (Itree a b));
```

```
data Pfun a b =
  Pfun_of_alist [(a, b)] |
  Pfun_of_map (a -> Maybe b) |
  Pfun_entries (Set.Set a) (a -> b);
```

```
lemma dom_pfun_alist [simp, code]:
  "pdom (pfun_of_alist xs) = set (map fst xs)"
  by (transfer, simp add: dom_map_of_conv_image_fst)
```

[1]Haftmann F., Nipkow, T.: Code Generation via Higher-Order Rewrite Systems. FLOPS (2010)

Needham-Schroeder Public-Key Protocol (NSPK)

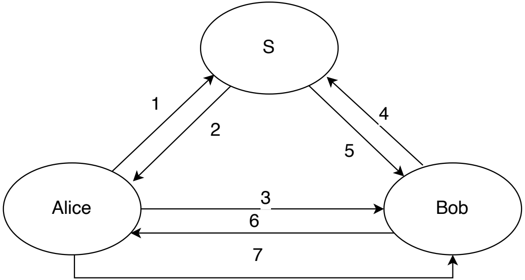
1978, Roger Needham and Michael Schroeder[1]

Establish secure communication between two parties over an insecure network

[1] Roger M. Needham and Michael D. Schroeder. 1978. Using encryption for authentication in large networks of computers. Commun. ACM 21, 12 (Dec. 1978)

Needham-Schroeder Public-Key Protocol (NSPK)

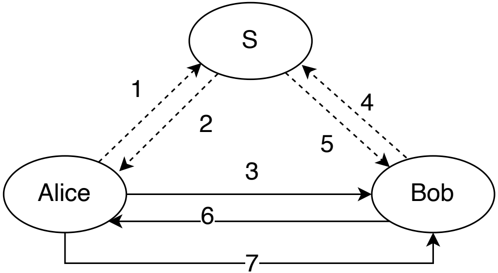
1. $A \rightarrow S : (A, B)$
2. $S \rightarrow A : \{\!|(pk(B), B)|\!\}^{s}_{sk(S)}$
3. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$
4. $B \rightarrow S : (B, A)$
5. $S \rightarrow B : \{\!|(pk(A), A)|\!\}^{s}_{sk(S)}$
6. $B \rightarrow A : \{\!|(na, nb)|\!\}_{pk(A)}$
7. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$



Messages 1,2,4,5 to retrieve public keys and Messages 3, 6, 7 for authentication

NSPK three-message version

1. $A \rightarrow S : (A, B)$
2. $S \rightarrow A : \{\!|(pk(B), B)|\!\}^{s}_{sk(S)}$
3. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$: assume both A and B knows each other's public key
4. $B \rightarrow S : (B, A)$
5. $S \rightarrow B : \{\!|(pk(A), A)|\!\}^{s}_{sk(S)}$
6. $B \rightarrow A : \{\!|(na, nb)|\!\}_{pk(A)}$
7. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$



NSPK three-message version

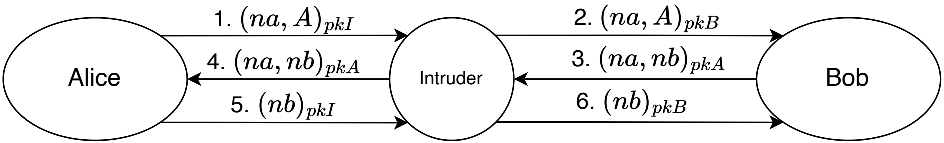
The man-in-the-middle-attack[1]: assume public keys are known to all principals

1. $A \rightarrow I : \{\!|(na, A)|\!\}_{pk(I)}$
2. $I(A) \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$: I pretends to be A
3. $B \rightarrow I(A) : \{\!|(na, nb)|\!\}_{pk(A)}$
4. $I \rightarrow A : \{\!|(na, nb)|\!\}_{pk(A)}$
5. $A \rightarrow I : \{\!|nb|\!\}_{pk(I)}$
6. $I(A) \rightarrow B : \{\!|nb|\!\}_{pk(B)}$: B believes that A has correctly established a session (shared secret (na, nb)) with him, but actually not

[1] Lowe, G. (1995). An attack on the Needham-Schroeder public-key authentication protocol. In IPL.

NSPK three-message version

The man-in-the-middle-attack[1]: assume public keys are known to all principals



[1] Lowe, G. (1995). An attack on the Needham-Schroeder public-key authentication protocol. In IPL.

Security Properties

Secrecy or confidentiality

The attacker cannot derive na and nb

Authenticity

Authentication for the initiator A:

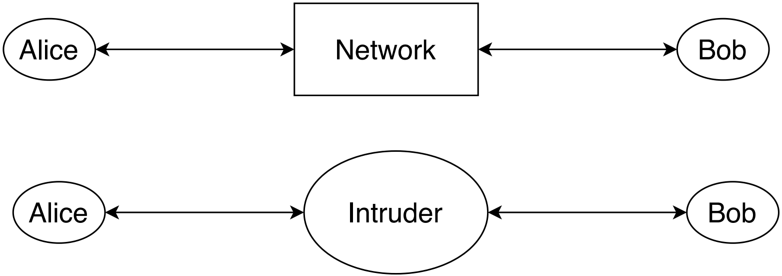
- A commits to a session with B only if B took part in the protocol run

Authentication for the responder B:

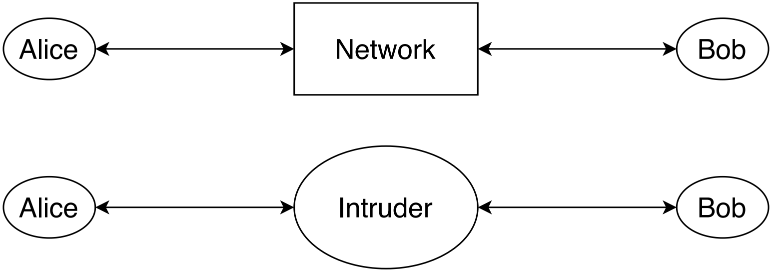
- B commits to a session with A only if A took part in the protocol run

Modelling of Protocols

Modelling of Protocols



Modelling of Protocols



PAlice $\|_A$ PIntruder $\|_B$ PBob

Dolev-Yao model[1]

The attacker controls the entire network and can

- intercept, delete, modify, delay, inject, and build new messages.

but limited by the cryptography and cannot

- decrypt messages without knowing the key. perfect blackbox cryptography

[1] D. Dolev and A. Yao, "On the security of public key protocols," in IEEE Transactions on Information Theory, vol. 29, no. 2, pp. 198-208, March 1983

Intruder message inference rules

$K \vdash_{\Downarrow} m$ - what the intruder can learn from a set of known messages K; Passive attacker

$K \vdash_{\Uparrow} m$ - what the intruder can build/fake from a set of known messages K

$\left\{m \mid \left(K \vdash_{\Downarrow} m\right)\right\} \vdash_{\Uparrow} m$: Active attacker

Name	Premise	Break down	Build up
Member	$m \in K$	$K \vdash_{\Downarrow} m$	$K \vdash_{\Uparrow} m$
Pairing	$m \in K \wedge m' \in K$		$K \vdash_{\Uparrow} (m, m')$
Unpairing	$(m, m') \in K$	$K \vdash_{\Downarrow} m$ and $K \vdash_{\Downarrow} m$	
Encryption/Sign	$m \in K \wedge k \in K$		$K \vdash_{\Uparrow} \{m\}_k$
Decryption/Verify	$\{m\}_k \in K \wedge k^{-1} \in K$	$K \vdash_{\Downarrow} m$	

Modelling of NSPK3 - type definitions

```
datatype dagent = Alice | Bob | Intruder
datatype dnonce = N dagent
datatype dpkey = PK dagent
datatype dskey = SK dagent
datatype dkey = Kp dpkey | Ks dskey
datatype dmsg = MAg (ma:dagent) | MNon (mn:dnonce) | MKp (mkp:dpkey) |
  MKs (mks:dskey) | MCmp (mc1:dmsg) (mc2:dmsg) |
  MEnc (mem:dmsg) (mek:dpkey)
```

Modelling of NSPK3 - type definitions

Used to specify and verify properties

```
datatype dsig = StartProt dagent dagent dnonce dnonce
  | EndProt dagent dagent dnonce dnonce
  | ClaimSecret (sag:dagent) (sn:dnonce) (sp: "ℙ dagent")
```

Modelling of NSPK3 - type definitions

Channels for communication between processes

```
datatype Chan =
  env :: dagent×dagent
  send, recv, hear, fake :: dagent×dagent×dmsg
  leak :: dmsg
  sig :: dsig
  terminate :: unit
```

Modelling of NSPK3

Protocol

1. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$
2. $B \rightarrow A :$
   $\{\!|(na, nb)|\!\}_{pk(A)}$
3. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$

$$
\begin{aligned}
& PAlice(A, na) \mathrel{\widehat=} \\
& \qquad env!A?B \rightarrow \\
& \qquad sig!ClaimSecrect!A!na!\{B\} \rightarrow \\
& \qquad send!\langle na, A\rangle_{pk(B)} \rightarrow \\
& \qquad recv?m : \{\langle na, nb\rangle_{pk(A)}\} \rightarrow \\
& \qquad sig!StartProt!A!B!na!nb \rightarrow \\
& \qquad send!nb_{pk(B)} \rightarrow \\
& \qquad sig!EndProt!A!B!na!nb \rightarrow \\
& \qquad terminate
\end{aligned}
$$

Modelling of NSPK3

Protocol

1. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$
2. $B \rightarrow A :$
   $\{\!|(na, nb)|\!\}_{pk(A)}$
3. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$

$$
\begin{aligned}
& PBob(B, nb) \mathrel{\widehat=} \\
& \quad recv?m : \{\langle na, A\rangle_{pk(B)}, \ldots\} \rightarrow \\
& \quad sig!ClaimSecrect!B!nb!\{A\} \rightarrow \\
& \quad sig!StartProt!B!A!na!nb \rightarrow \\
& \quad send!\langle na, nb\rangle_{pk(A)} \rightarrow \\
& \quad recv?m : \{nb_{pk(B)}\} \rightarrow \\
& \quad sig!EndProt!B!A!na!nb \rightarrow \\
& \quad terminate
\end{aligned}
$$

Modelling of NSPK3

Protocol

1. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$
2. $B \rightarrow A : \{\!|(na, nb)|\!\}_{pk(A)}$
3. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$

$$
\begin{array}{l}
PIntruder(I, ni, kn, ss) \mathrel{\widehat=} \\
\quad hear?m \rightarrow PIntruder(I, ni, breakm(kn \cup \{m\}), ss) \\
\quad \Box\ (\Box\ m : build_n(kn) \bullet fake!m \rightarrow PIntruder(I, ni, kn, ss)) \\
\quad \Box\ (\Box\ s : ss \cap kn \bullet leak!s \rightarrow PIntruder(I, ni, kn, ss)) \\
\quad \Box\ terminate \rightarrow Skip
\end{array}
$$

Modelling of NSPK3

NSPK3 protocol

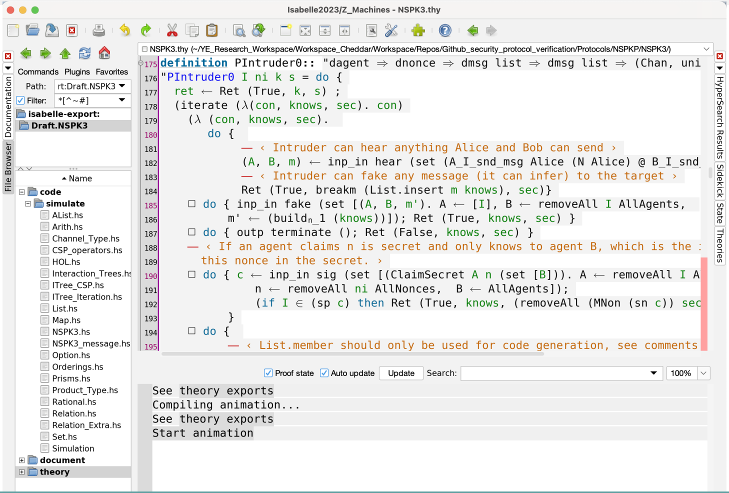
Protocol

1. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$
2. $B \rightarrow A :$ $\{\!|(na, nb)|\!\}_{pk(A)}$
3. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$

$$
\begin{aligned}
initknows &\mathrel{\widehat{=}} Agents \cup PublicKeys \cup \{ni, sk_I\} \\
secrets &\mathrel{\widehat{=}} \{na, nb\} \\
NSPK3 &\mathrel{\widehat{=}} \\
&\qquad \Big(PAlice(Alice, na) \parallel_{\{terminte\}} PBob(Bob, nb)\Big) \\
&\qquad \parallel_{\{\!|send, recv, terminate|\!\}} \\
&\qquad PIntruder(I, ni, initknows, secrets) \\
&\qquad\quad [hear \leftarrow send, fake \leftarrow recv]
\end{aligned}
$$

Demonstration

Automatic code generation from Isabelle/HOL



Demonstration

Manual exploration

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: 1
Env_C (Alice,Bob)
Events:
 (1) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (2) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;
 (3) Sig ClaimSecret Alice (N Alice) (Set [ Bob ]);

[Choose: 1-3]: 3
Sig_C (ClaimSecret Alice (N Alice) (Set [Bob]))
Events:
 (1) Send [Alice=>Intruder] {<N Alice, Alice>}_PK Bob;
 (2) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (3) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-3]: 1
Send_C (Alice,(Intruder,MEnc (MCmp (MNon (N Alice)) (MAg Alice)) (PK Bob)))
Events:
 (1) Recv [Bob<=Intruder] {<N Alice, Alice>}_PK Bob;
 (2) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (3) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;
```

Demonstration

Automatic modes

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: h
*** Usage ***
Auto n : Exhaustive search of traces up to n events or length;
Rand n : Random search of a trace up to n events or length;
AReach n %er1;er2;...%[#%em1;em2;...%] : Exhaustive search of traces up tc
RReach n %er1;er2;...%[#%em1;em2;...%] : Random search of a trace up to n
Feasible %event1;event2;...% : Check whether the specified sequence of eve
```

Demonstration

Termination

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: AReach 15 %Terminate%
AReach 15,  %Terminate%
Reachability by Auto: 15
  Events for reachability check: ["Terminate"]
  Events for monitor: []
...............................*** These events ["Terminate"] are reached! ***
Trace: [Env [Alice] Bob, Sig ClaimSecret Alice (N Alice) (Set [ Bob ]), Send [Alice=>Int
rot Bob Alice (N Alice) (N Bob), Send [Bob=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv
rot Alice Bob (N Alice) (N Bob), Recv [Bob<=Intruder] {N Bob}_PK Bob, Sig EndProt Bob Al

*** These events ["Terminate"] are reached! ***
Trace: [Env [Alice] Bob, Sig ClaimSecret Alice (N Alice) (Set [ Bob ]), Send [Alice=>Int
rot Bob Alice (N Alice) (N Bob), Send [Bob=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv
b<=Intruder] {N Bob}_PK Bob, Sig EndProt Bob Alice (N Alice) (N Bob), Sig EndProt Alice

*** These events ["Terminate"] are reached! ***
Trace: [Env [Alice] Bob, Sig ClaimSecret Alice (N Alice) (Set [ Bob ]), Send [Alice=>Int
rot Bob Alice (N Alice) (N Bob), Send [Bob=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv
b<=Intruder] {N Bob}_PK Bob, Sig EndProt Alice Bob (N Alice) (N Bob), Sig EndProt Bob Al
```

Demonstration

Secrecy

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: AReach 15 %Leak N Bob%
AReach 15,  %Leak N Bob%
Reachability by Auto: 15
  Events for reachability check: ["Leak N Bob"]
  Events for monitor: []
..........................................................................................
..........................................................................................
.......................................*** These events ["Leak N Bob"] are reached! ***
Trace: [Env [Alice] Intruder, Sig ClaimSecret Alice (N Alice) (Set [ Intruder ]), Send [A
lice=>Intruder] {<N Alice, Alice>}_PK Intruder, Recv [Bob<=Intruder] {<N Alice, Alice>}_P
K Bob, Sig ClaimSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N
Bob), Send [Bob=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice,
 N Bob>}_PK Alice, Sig StartProt Alice Intruder (N Alice) (N Bob), Send [Alice=>Intruder]
 {N Bob}_PK Intruder, ]

..........................................................................................
..........................................................................................
..........................................................................................
...................................*** Auto Reachability [15] Finished ***
```

Demonstration

User-guided verification

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: 1
Env_C (Alice,Bob)
Events:
 (1) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (2) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;
 (3) Sig ClaimSecret Alice (N Alice) (Set [ Bob ]);

[Choose: 1-3]: AReach 15 %Leak N Bob%
AReach 15,  %Leak N Bob%
Reachability by Auto: 15
  Events for reachability check: ["Leak N Bob"]
  Events for monitor: []
...........................................*** Auto Reachability [15] Finished ***
```

Demonstration

Authenticity for Alice

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: AReach 15 %Sig EndProt Alice Bob (N Alice) (N Bob)% # %Sig StartProt Bob A
lice (N Alice) (N Bob)%
AReach 15,  %Sig EndProt Alice Bob (N Alice) (N Bob)% # %Sig StartProt Bob Alice (N Alice
) (N Bob)%
Reachability by Auto: 15
  Events for reachability check: ["Sig EndProt Alice Bob (N Alice) (N Bob)"]
  Events for monitor: ["Sig StartProt Bob Alice (N Alice) (N Bob)"]
...............................*** These events ["Sig StartProt Bob Alice (N Alice) (N Bo
b)"] are monitored! ***
*** These events ["Sig EndProt Alice Bob (N Alice) (N Bob)"] are reached! ***
Trace: [Env [Alice] Bob, Sig ClaimSecret Alice (N Alice) (Set [ Bob ]), Send [Alice=>Intr
uder] {<N Alice, Alice>}_PK Bob, Recv [Bob<=Intruder] {<N Alice, Alice>}_PK Bob, Sig Clai
mSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N Bob), Send [Bob
=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Ali
ce, Sig StartProt Alice Bob (N Alice) (N Bob), Send [Alice=>Intruder] {N Bob}_PK Bob, ]

......................................................................................
.......*** These events ["Sig StartProt Bob Alice (N Alice) (N Bob)"] are monitored! ***
..*** These events ["Sig StartProt Bob Alice (N Alice) (N Bob)"] are monitored! ***
.*** These events ["Sig StartProt Bob Alice (N Alice) (N Bob)"] are monitored! ***
..*** These events ["Sig StartProt Bob Alice (N Alice) (N Bob)"] are monitored! ***
.....*** These events ["Sig StartProt Bob Alice (N Alice) (N Bob)"] are monitored! ***
 *** These events ["Sig StartProt Bob Alice (N Alice) (N Bob)"] are monitored! ***
```

Demonstration

Authenticity for Bob

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: AReach 15 %Sig EndProt Bob Alice (N Alice) (N Bob)% # %Sig StartProt Alice Bob (N Alice) (N Bob)%
AReach 15,  %Sig EndProt Bob Alice (N Alice) (N Bob)% # %Sig StartProt Alice Bob (N Alice) (N Bob)%
Reachability by Auto: 15
  Events for reachability check: ["Sig EndProt Bob Alice (N Alice) (N Bob)"]
  Events for monitor: ["Sig StartProt Alice Bob (N Alice) (N Bob)"]
...............................*** These events ["Sig StartProt Alice Bob (N Alice) (N Bob)"] are monitored! ***
*** These events ["Sig EndProt Bob Alice (N Alice) (N Bob)"] are reached! ***
Trace: [Env [Alice] Bob, Sig ClaimSecret Alice (N Alice) (Set [ Bob ]), Send [Alice=>Intruder] {<N Alice, Alice>}_PK Bob, Recv [Bob<=Intruder
] {<N Alice, Alice>}_PK Bob, Sig ClaimSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N Bob), Send [Bob=>Intruder] {<N
 Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Alice, Sig StartProt Alice Bob (N Alice) (N Bob), Send [Alice=>Intrude
r] {N Bob}_PK Bob, Sig EndProt Alice Bob (N Alice) (N Bob), Recv [Bob<=Intruder] {N Bob}_PK Bob, ]

*** These events ["Sig EndProt Bob Alice (N Alice) (N Bob)"] are reached! ***
Trace: [Env [Alice] Bob, Sig ClaimSecret Alice (N Alice) (Set [ Bob ]), Send [Alice=>Intruder] {<N Alice, Alice>}_PK Bob, Recv [Bob<=Intruder
] {<N Alice, Alice>}_PK Bob, Sig ClaimSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N Bob), Send [Bob=>Intruder] {<N
 Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Alice, Sig StartProt Alice Bob (N Alice) (N Bob), Send [Alice=>Intrude
r] {N Bob}_PK Bob, Recv [Bob<=Intruder] {N Bob}_PK Bob, ]

..............................................................................................................................................
.............................................*** These events ["Sig EndProt Bob Alice (N Alice) (N Bob)"] are reached! ***
Trace: [Env [Alice] Intruder, Sig ClaimSecret Alice (N Alice) (Set [ Intruder ]), Send [Alice=>Intruder] {<N Alice, Alice>}_PK Intruder, Recv
 [Bob<=Intruder] {<N Alice, Alice>}_PK Bob, Sig ClaimSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N Bob), Send [Bob
=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Alice, Sig StartProt Alice Intruder (N Alice) (N Bob),
Send [Alice=>Intruder] {N Bob}_PK Intruder, Leak N Bob, Sig EndProt Alice Intruder (N Alice) (N Bob), Recv [Bob<=Intruder] {N Bob}_PK Bob, ]

*** These events ["Sig EndProt Bob Alice (N Alice) (N Bob)"] are reached! ***
Trace: [Env [Alice] Intruder, Sig ClaimSecret Alice (N Alice) (Set [ Intruder ]), Send [Alice=>Intruder] {<N Alice, Alice>}_PK Intruder, Recv
 [Bob<=Intruder] {<N Alice, Alice>}_PK Bob, Sig ClaimSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N Bob), Send [Bob
=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Alice, Sig StartProt Alice Intruder (N Alice) (N Bob),
Send [Alice=>Intruder] {N Bob}_PK Intruder, Leak N Bob, Recv [Bob<=Intruder] {N Bob}_PK Bob, ]

*** These events ["Sig EndProt Bob Alice (N Alice) (N Bob)"] are reached! ***
Trace: [Env [Alice] Intruder, Sig ClaimSecret Alice (N Alice) (Set [ Intruder ]), Send [Alice=>Intruder] {<N Alice, Alice>}_PK Intruder, Recv
 [Bob<=Intruder] {<N Alice, Alice>}_PK Bob, Sig ClaimSecret Bob (N Bob) (Set [ Alice ]), Sig StartProt Bob Alice (N Alice) (N Bob), Send [Bob
=>Intruder] {<N Alice, N Bob>}_PK Alice, Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Alice, Sig StartProt Alice Intruder (N Alice) (N Bob),
Send [Alice=>Intruder] {N Bob}_PK Intruder, Sig EndProt Alice Intruder (N Alice) (N Bob), Leak N Bob, Recv [Bob<=Intruder] {N Bob}_PK Bob, ]
```

Demonstration

Automatic feasibility check

```
Starting ITree Animation...
Events:
 (1) Env [Alice] Bob;
 (2) Env [Alice] Intruder;
 (3) Recv [Bob<=Intruder] {<N Intruder, Alice>}_PK Bob;
 (4) Recv [Bob<=Intruder] {<N Intruder, Intruder>}_PK Bob;

[Choose: 1-4]: Feasible %Env [Alice] Intruder; Sig ClaimSecret Alice (N Alice) (Set [ Intruder
 ]); Send [Alice=>Intruder] {<N Alice, Alice>}_PK Intruder; Recv [Bob<=Intruder] {<N Alice, Al
ice>}_PK Bob; Sig ClaimSecret Bob (N Bob) (Set [ Alice ]); Sig StartProt Bob Alice (N Alice) (
N Bob); Send [Bob=>Intruder] {<N Alice, N Bob>}_PK Alice; Recv [Alice<=Intruder] {<N Alice, N
Bob>}_PK Alice; Sig StartProt Alice Intruder (N Alice) (N Bob); Send [Alice=>Intruder] {N Bob}
_PK Intruder; Leak N Bob%
Feasible,  %Env [Alice] Intruder; Sig ClaimSecret Alice (N Alice) (Set [ Intruder ]); Send [Al
ice=>Intruder] {<N Alice, Alice>}_PK Intruder; Recv [Bob<=Intruder] {<N Alice, Alice>}_PK Bob;
 Sig ClaimSecret Bob (N Bob) (Set [ Alice ]); Sig StartProt Bob Alice (N Alice) (N Bob); Send
[Bob=>Intruder] {<N Alice, N Bob>}_PK Alice; Recv [Alice<=Intruder] {<N Alice, N Bob>}_PK Alic
e; Sig StartProt Alice Intruder (N Alice) (N Bob); Send [Alice=>Intruder] {N Bob}_PK Intruder;
 Leak N Bob%
Feasibility check the sequence of events: ["Env [Alice] Intruder","Sig ClaimSecret Alice (N Al
ice) (Set [ Intruder ])","Send [Alice=>Intruder] {<N Alice, Alice>}_PK Intruder","Recv [Bob<=I
ntruder] {<N Alice, Alice>}_PK Bob","Sig ClaimSecret Bob (N Bob) (Set [ Alice ])","Sig StartPr
ot Bob Alice (N Alice) (N Bob)","Send [Bob=>Intruder] {<N Alice, N Bob>}_PK Alice","Recv [Alic
e<=Intruder] {<N Alice, N Bob>}_PK Alice","Sig StartProt Alice Intruder (N Alice) (N Bob)","Se
nd [Alice=>Intruder] {N Bob}_PK Intruder","Leak N Bob"]
*** The specified trace is feasible ****
```

Evaluation

NSPK3: secrecy and authenticity for Bob are violated

NSLPK3 - Lowe's corrected version[1]: safe

1. $A \rightarrow B : \{\!|(na, A)|\!\}_{pk(B)}$
2. $B \rightarrow A : \{\!|(na, nb, B)|\!\}_{pk(A)}$
3. $A \rightarrow B : \{\!|nb|\!\}_{pk(B)}$

DH: used the animation to find the similar man-in-the-middle-attack (several counterexamples)

DH with digital signature: not subject to the same attack

[1] Gavin Lowe. 1996. Breaking and Fixing the Needham-Schroeder Public-Key Protocol Using FDR. In (TACAs '96).

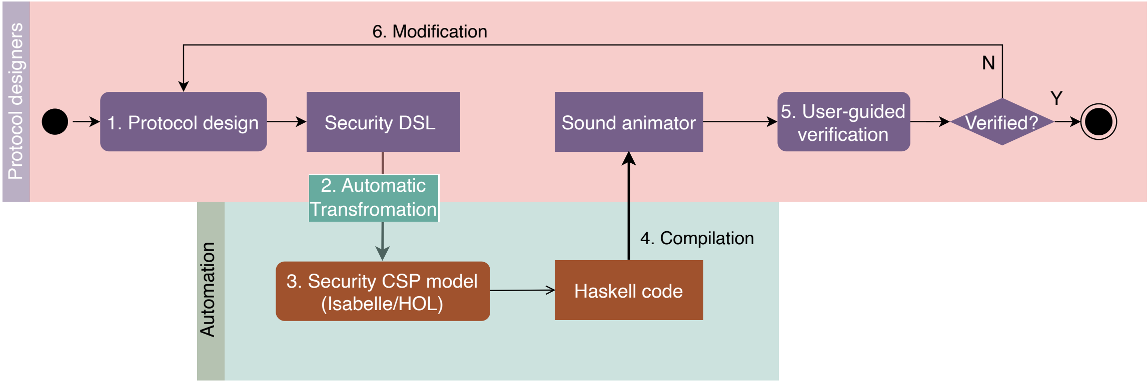
Conclusions

- Proposed an iterative workflow to support verification by designers through sound animation
- Enhanced animator to be a lightweight model checker: reachability and feasibility
- Verified two security protocols: NSPK and DH, and their corrected variants

Future work

- Generalisation of the framework for animation of security protocols
- Case studies
  - Physical layer security: watermarking and jamming, as security mechanism for IoT devices in edge-computing networks
  - 5G EAP-TLS, 5G AKA
  - Mesh Commissioning Protoco (MeshCoP) for the Thread network protocol
- Improvement of UI

Current not fully accessible → Fully automated workflow



Current limitations → Theorem Proving: (ITree-based) CSP and Circus

Limitations

- Enumerable and finite data types: agents, nonces, etc. Finite number of sessions
- Intensive space and computation time requirements to infer messages for the intruder

Animation can only verify a protocol with finite agents and bounded message inference in a finite number of interactions or steps. These are due to the executable nature of animation.

Current limitations → Theorem Proving: (ITree-based) CSP and Circus

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- Enumerable and finite data types: agents, nonces, etc. Finite number of sessions
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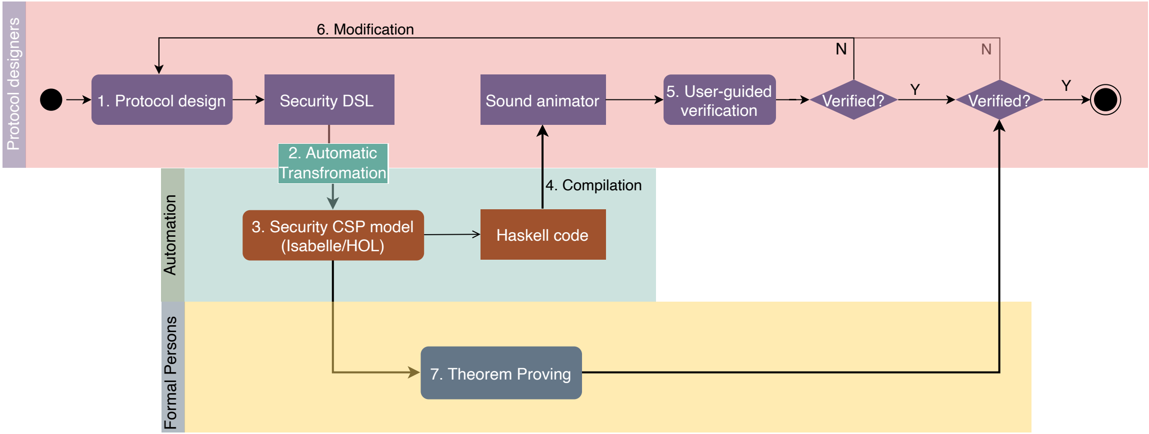
Animation can only verify a protocol with finite agents and bounded message inference in a finite number of interactions or steps. These are due to the executable nature of animation.

However, these are not the limitations of ITrees and ITree-based CSP.

Combined sound animation with theorem proving

- ITree-based CSP or Circus: could be for deductive verification
- General CSP or Circus: with nondeterministic and refinement

Current limitations → Theorem Proving: (ITree-based) CSP and Circus



Thank you!

https://www-users.york.ac.uk/~ky582/

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