Efficient verification of observational equivalences in finite process calculi

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Inria Nancy Grand-Est

Security protocols

TLS

Wifi

E-voting

E-passport

Security protocols

TLS

2016 (early ver. 1.3)

Wifi

2017 (WPA2)

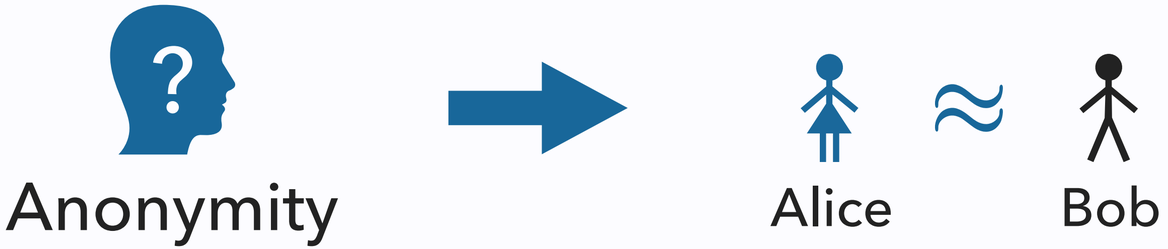
E-voting

2010 (Helios)

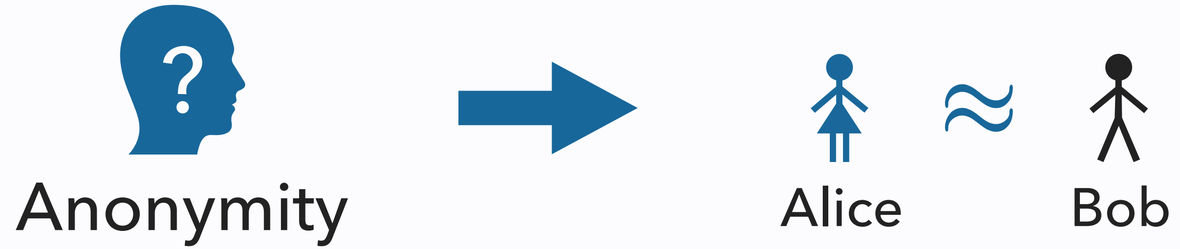
E-passport

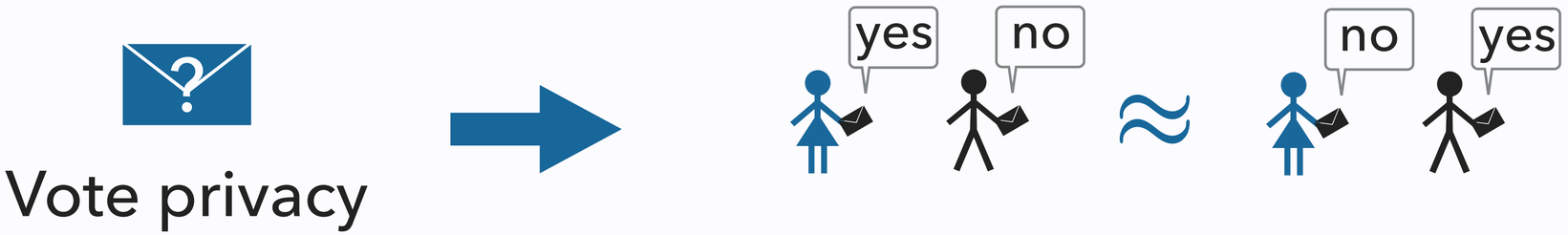
2013 (BAC)

Privacy as indistinguishability



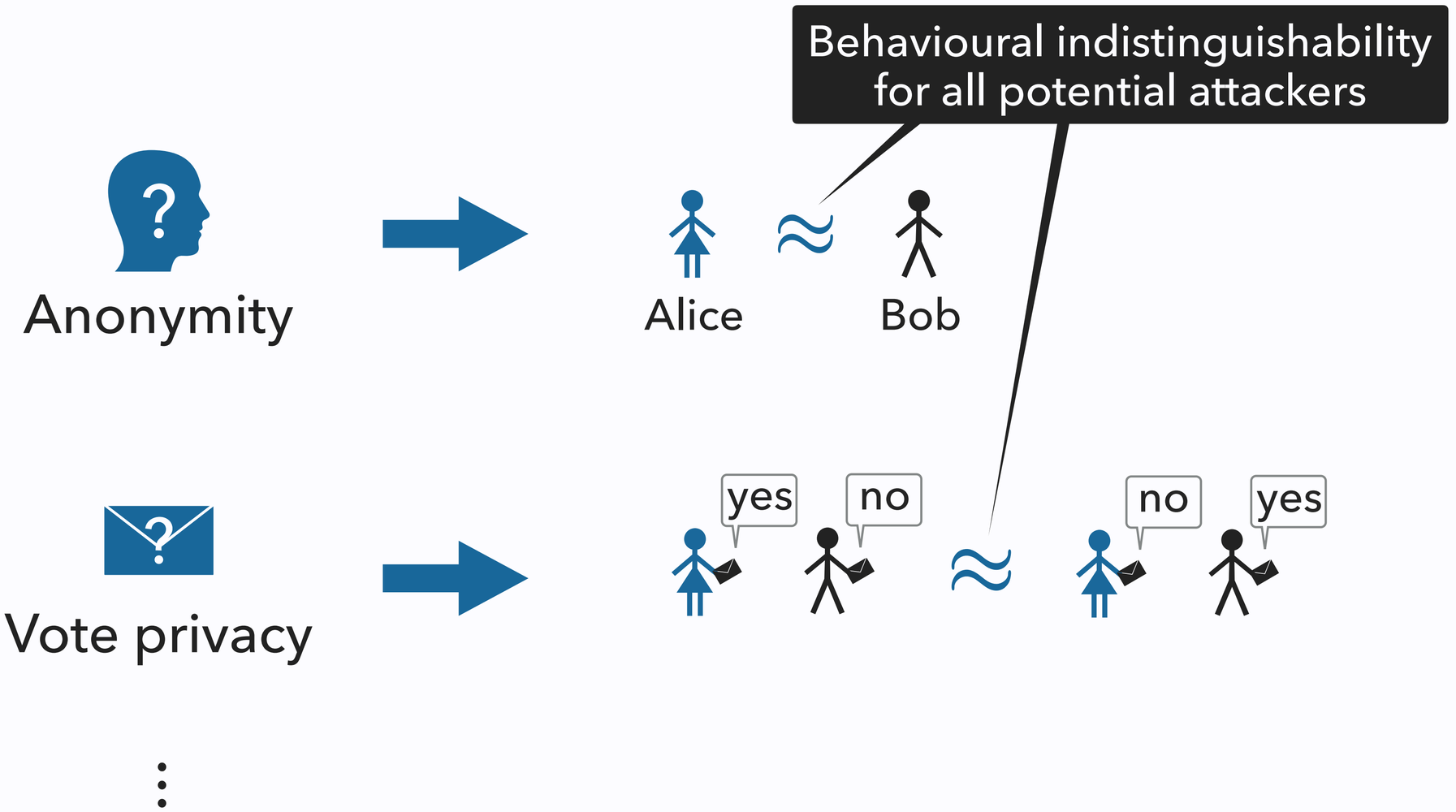
Privacy as indistinguishability





⋮

Privacy as indistinguishability



Privacy as indistinguishability

Privacy as indistinguishability

☹ Equivalence coNEXP-complete

for a fixed number of participants

📖 **[S&P18]** S. Kremer, V. Cheval, I. Rakotonirina.

DEEPSEC: Deciding equivalence properties in security protocols – theory and practice

Privacy as indistinguishability

Equivalence coNEXP-complete

for a fixed number of participants

[S&P18] S. Kremer, V. Cheval, I. Rakotonirina.

DEEPSEC: Deciding equivalence properties in security protocols – theory and practice

Observation

Each time, the two processes share a common structure

Contributions

- A refinement of trace equivalence
  for processes with structural similarities
- Partial-order reductions
  for any process for this new equivalence
- Integration into the DeepSec prover

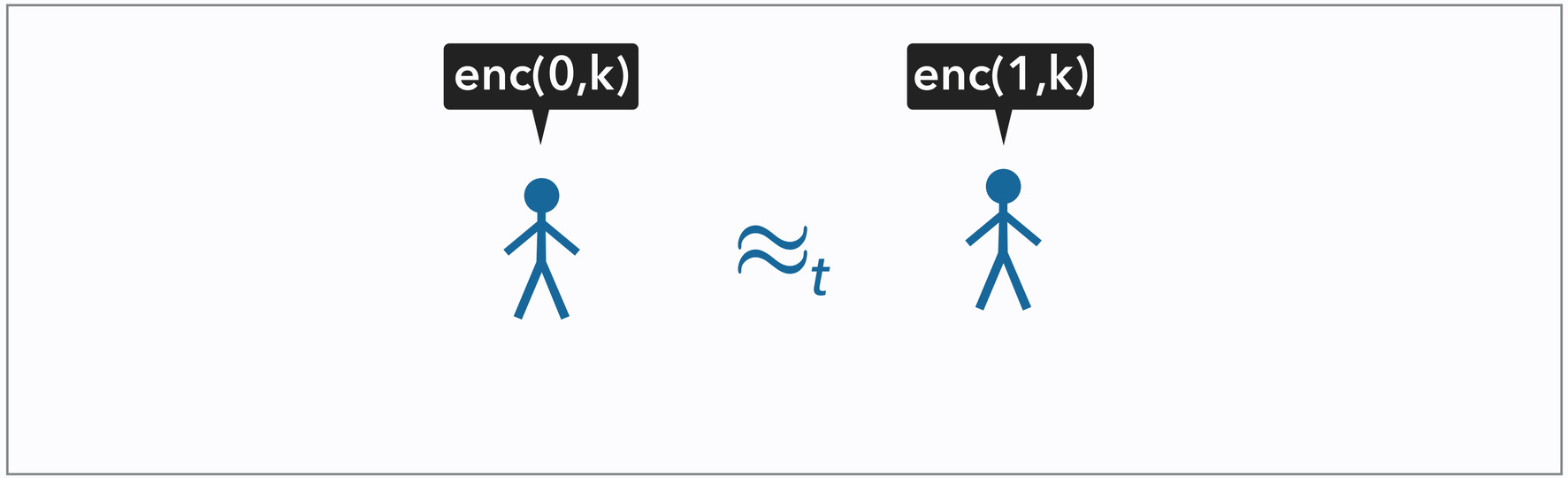
Trace equivalence

Modelling indistinguishability

A simple example

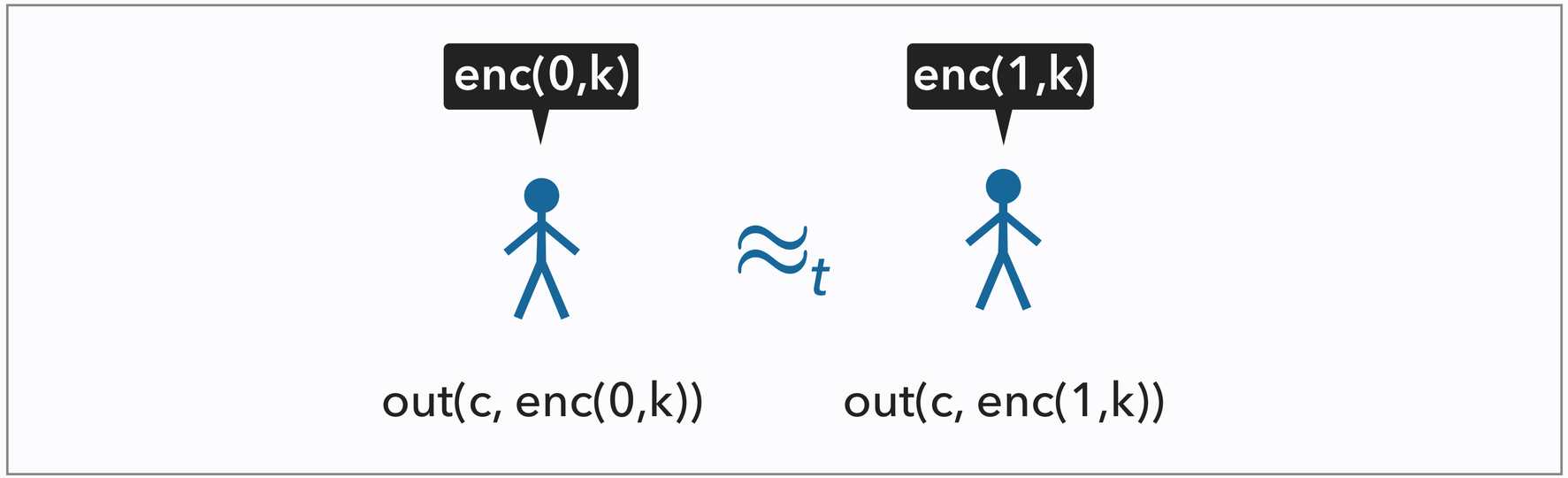
Modelling indistinguishability

A simple example



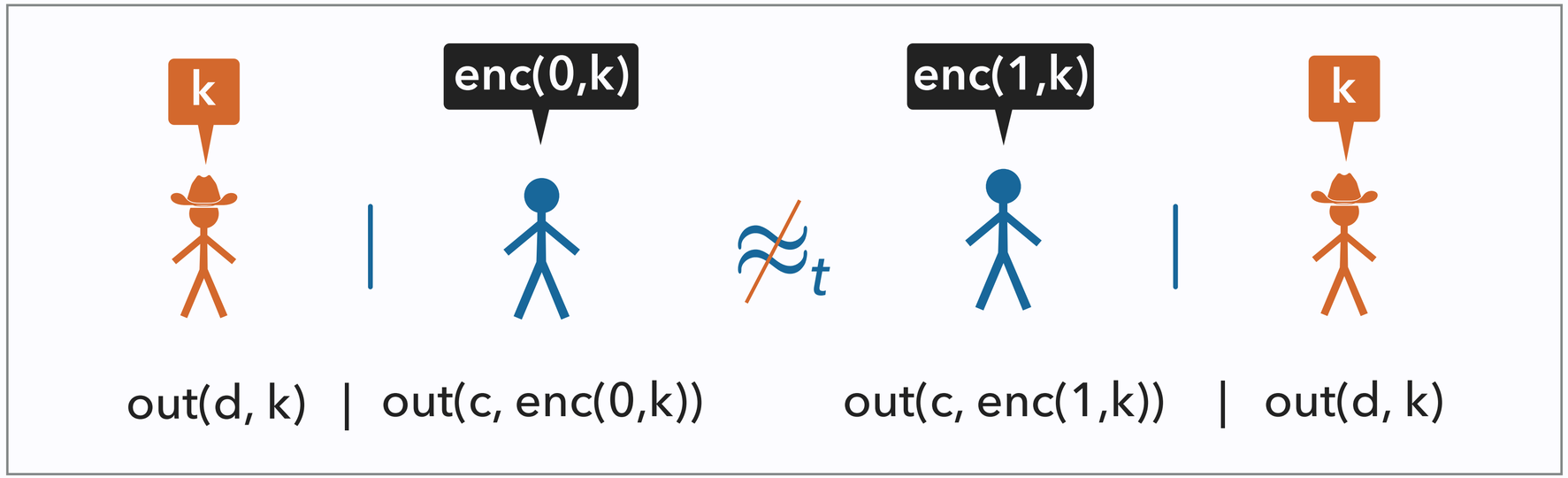
Modelling indistinguishability

A simple example



Modelling indistinguishability

A simple example



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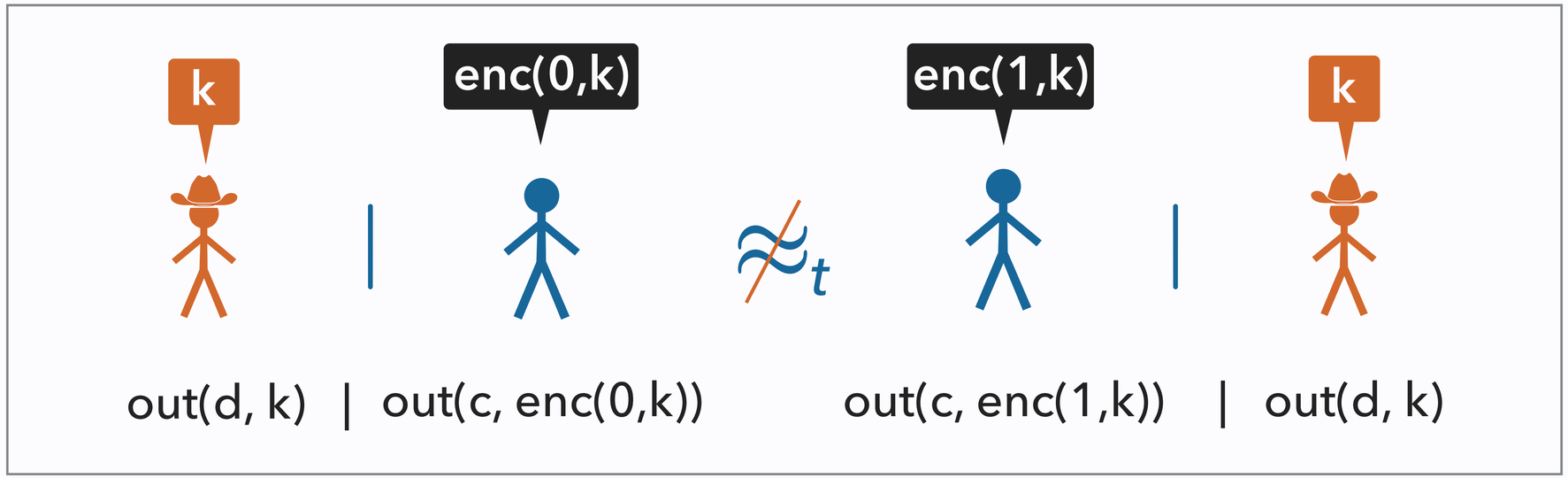
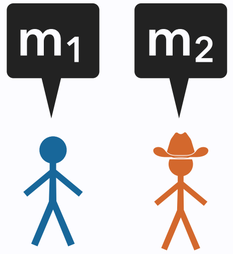
A simple example

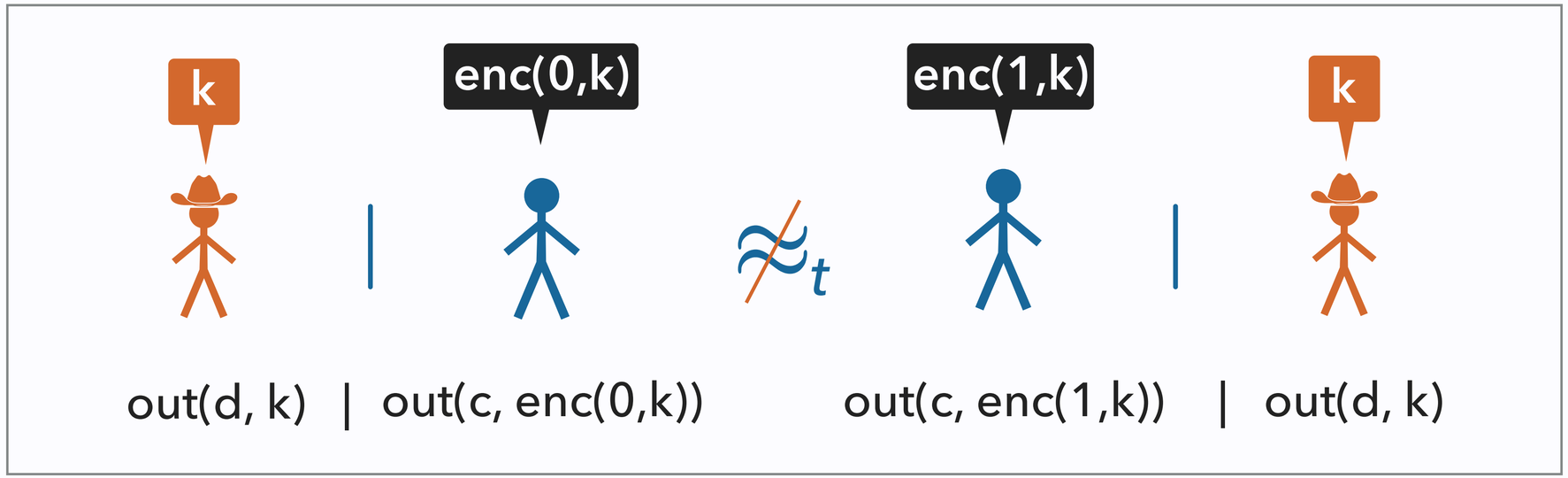


Distinguishing execution:



Modelling indistinguishability

A simple example



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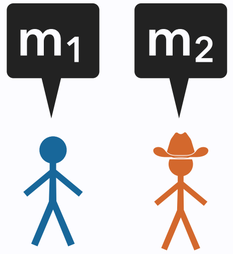

+ test $\mathrm{dec}(m_1,m_2) \stackrel{?}{=} 0$

Modelling indistinguishability

Formalism

$$P_0 \approx_t P_1 \quad \textit{iff} \quad \forall\, t \in \mathrm{Traces}(P_i),\ \exists\, t' \in \mathrm{Traces}(P_{1-i}),\ t \sim t'$$

Modelling indistinguishability

Formalism

algebra of **finite concurrent processes**

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sequences of inputs/outputs in an active adversarial environment

Modelling indistinguishability

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sequences of inputs/outputs in an active adversarial environment

Output ⇒ increases the attacker's knowledge

Input ⇒ receives a term from the attacker

Modelling indistinguishability

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sequences of inputs/outputs in an active adversarial environment

static indistinguishability of sequences of inputs/outputs

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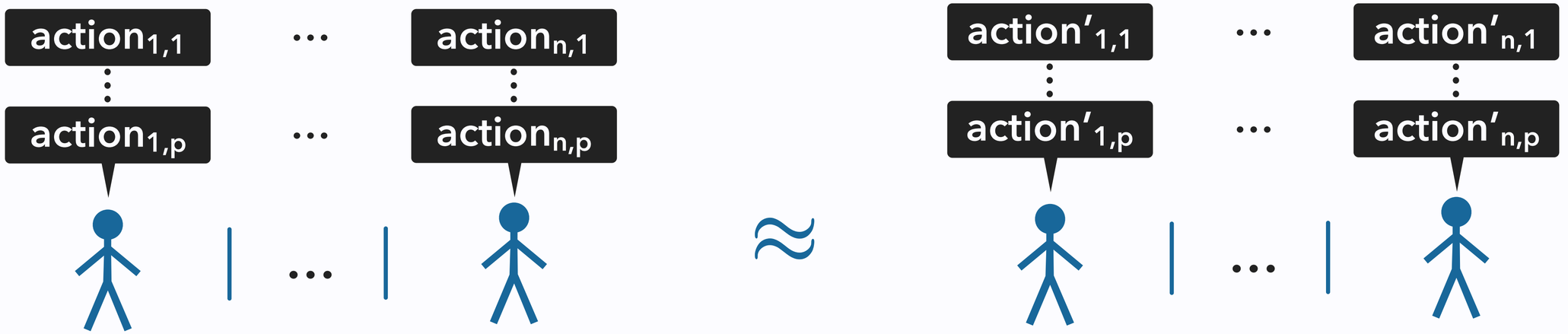
Input ⇒ receives a term from the attacker

Trace equivalence… in practice

A combinatorial fact



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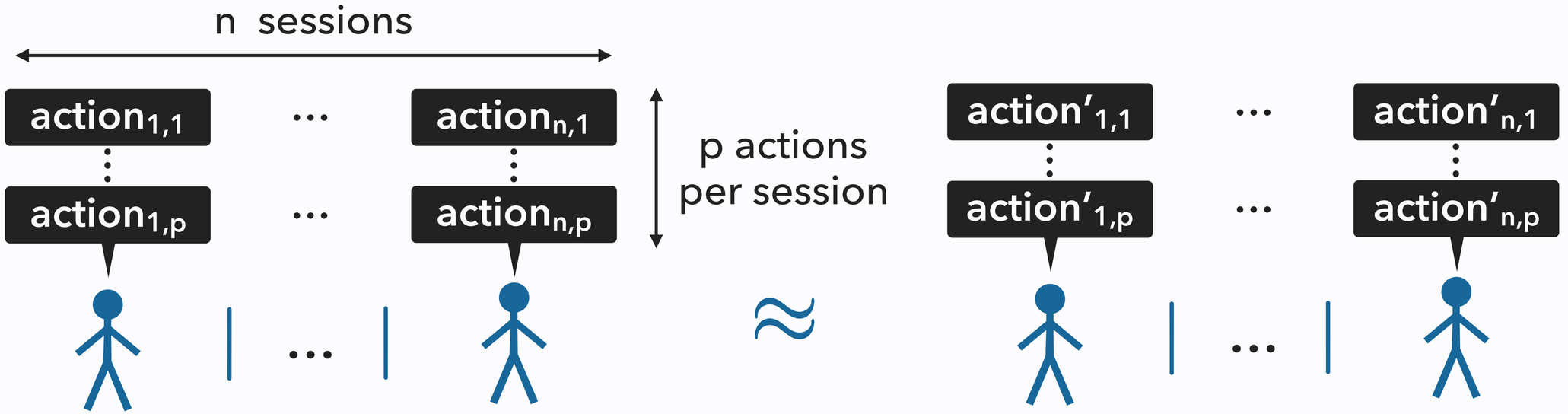

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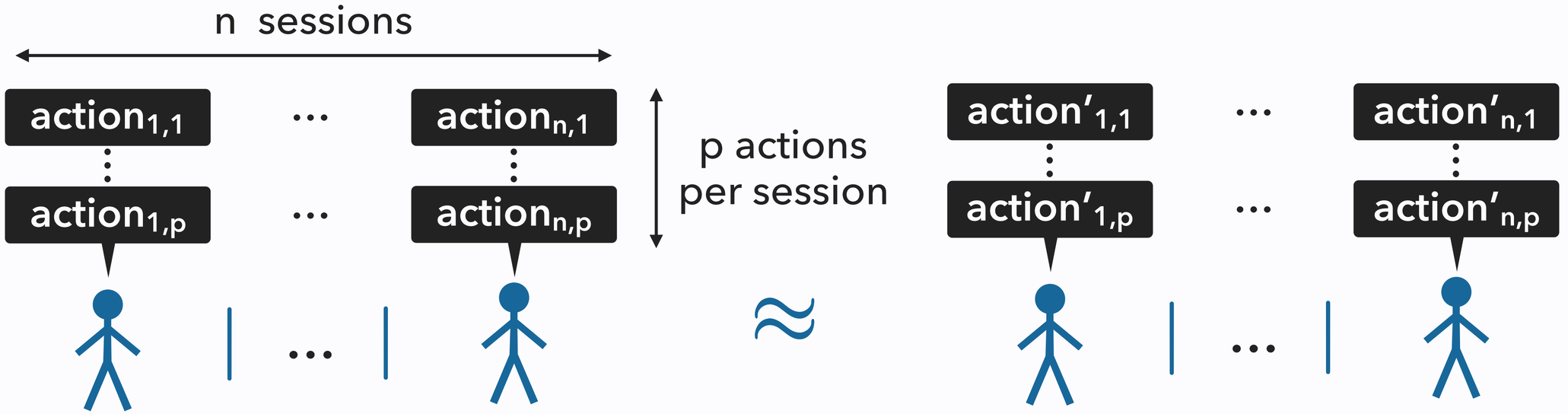
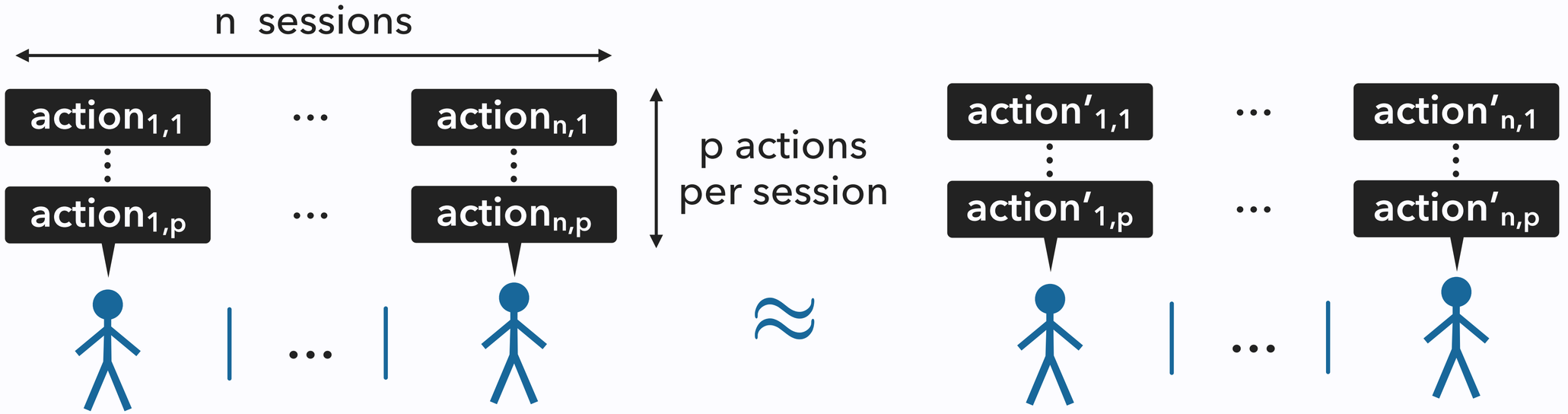


Goal ∀ sequences $[a_1\ a_2 \ldots a_{np}]$, ∃ equivalent sequence $[a'_1\ a'_2 \ldots a'_{np}]$

A combinatorial fact



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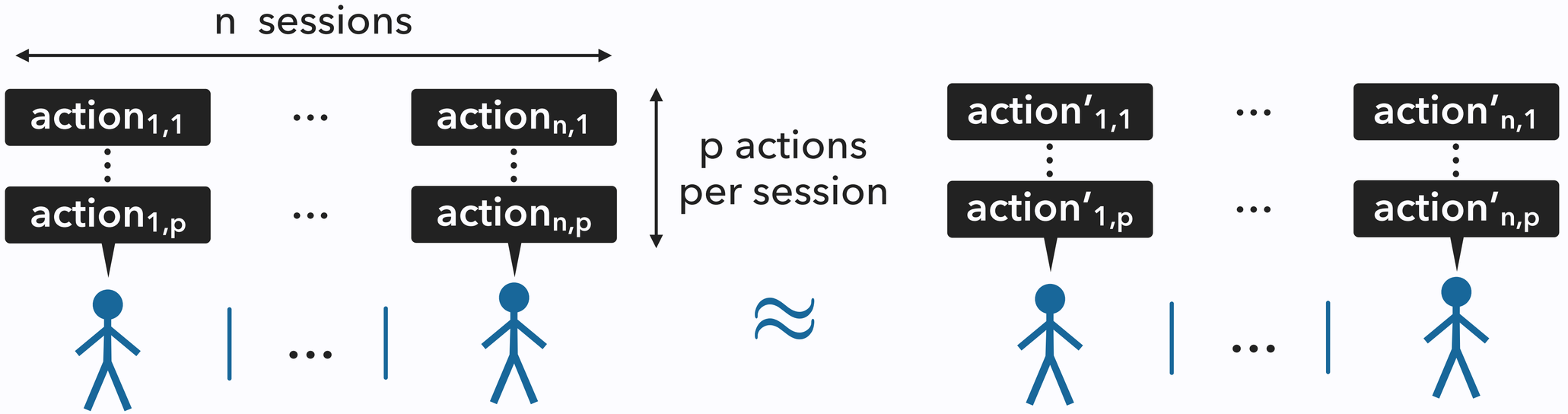
~(np)! matchings

Actions

A combinatorial fact



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~(np)! matchings

Actions

~n! matchings

Sessions

Formally: process pairing

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(MATCH) $(P_1 \mid \ldots \mid P_n, Q_1 \mid \ldots \mid Q_n) \longrightarrow (P_1, Q_{\sigma(1)}), \ldots, (P_n, Q_{\sigma(n)})$

σ permutation of $\{1,\ldots,n\}$

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(EXEC) $(P,Q) \xrightarrow{\alpha} (P',Q')$ if $P \xrightarrow{\alpha} P'$ and $Q \xrightarrow{\alpha} Q'$ (in the single-process semantics)

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Equiv. by session + $\exists\, t^2 \in \text{Traces}(P,Q),\ \text{fst}(t^2) = t \text{ and } \text{snd}(t^2) = t'$

Optimisations

For trace equivalence

[CONCUR15] D. Baelde, S. Delaune, L. Hirschi.

Partial-order reductions for security protocols

For trace equivalence

[CONCUR15] D. Baelde, S. Delaune, L. Hirschi.

Partial-order reductions for security protocols

$$\forall\, t \in \mathsf{Traces}(P), \quad \exists\, t' \in \mathsf{Traces}(Q),\ t \sim t'$$

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reduce the number of traces to check?

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Main theorem

If P,Q are determinate, it is sufficient to consider traces up to permutation of adjacent independent actions.

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Concurrent actions with no data flow

For equivalence by session

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$+\ \exists\, t^2 \in \mathrm{Traces}(P,Q),\ \mathrm{fst}(t^2) = t \text{ and } \mathrm{snd}(t^2) = t'$

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Concurrent actions with no data flow

Experiments

Approaches to prove trace equivalence

Approaches to prove trace equivalence

Baseline

P and Q trace equivalent?

Structure-guided

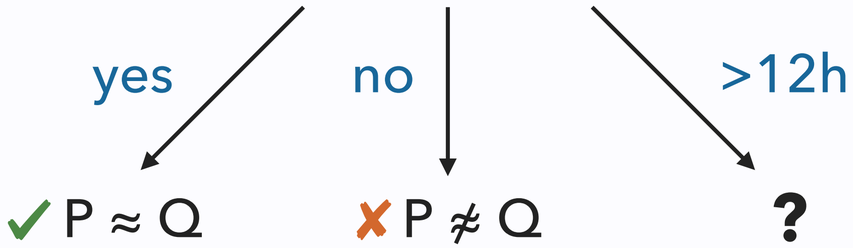
P and Q equivalent by session?

Approaches to prove trace equivalence

DEEPSEC

Baseline

P and Q trace equivalent?



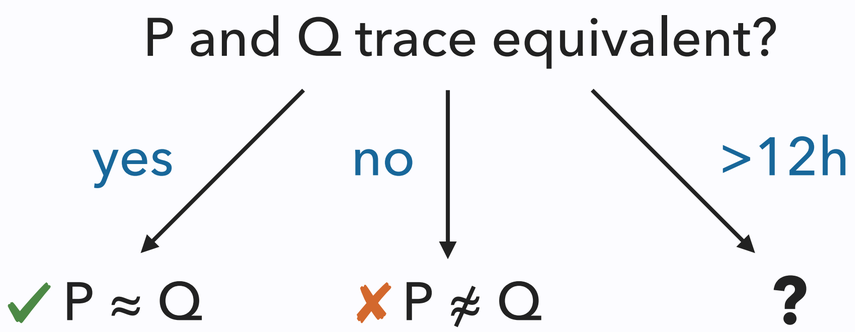
Structure-guided

P and Q equivalent by session?

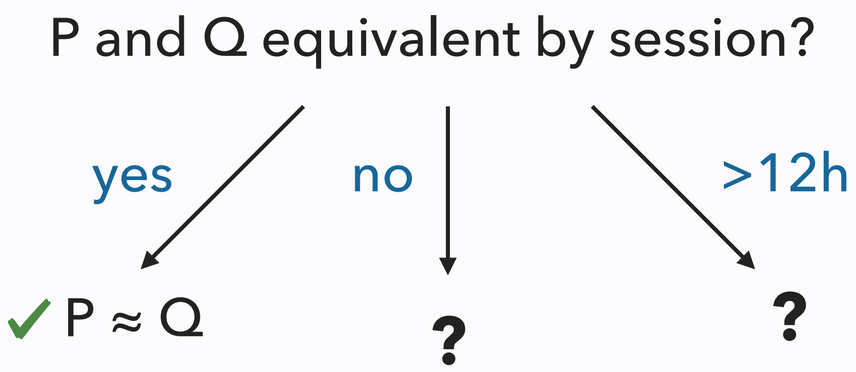
Approaches to prove trace equivalence

DEEPSEC

Baseline



Structure-guided



Approaches to prove trace equivalence

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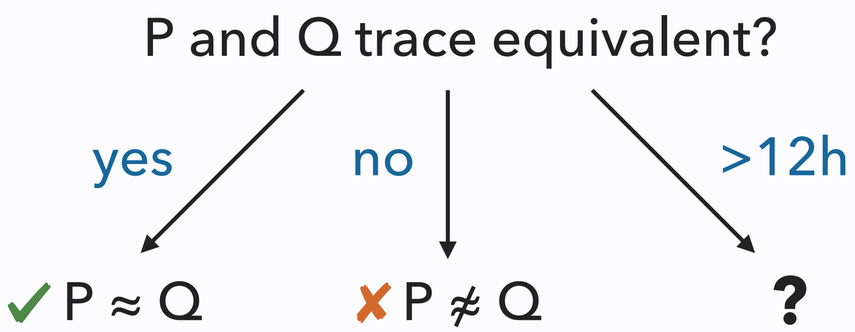
Baseline



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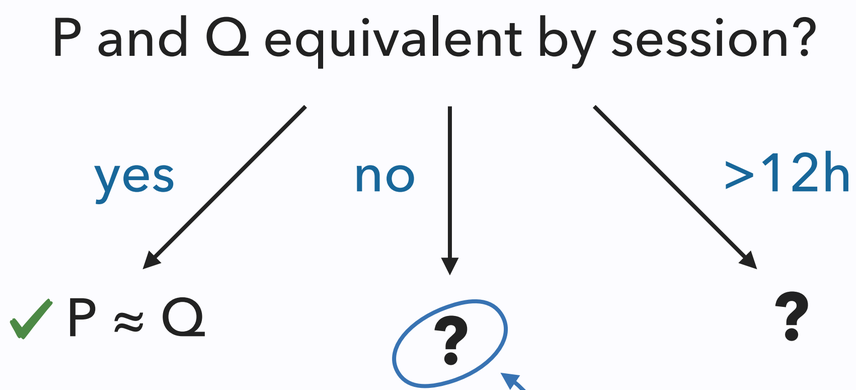

Ongoing work:

conclude in this case
(currently: heuristic)

Experimental results (1)

Unlinkability in the Electronic passport

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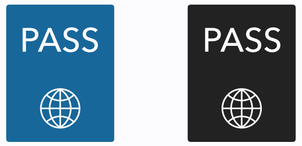
Unlinkability in the Electronic passport

2 identical passports

readers



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DEEPSEC

v1.0.2

Experimental results (1)

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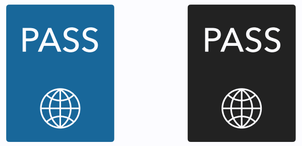


2 different passports

readers

Scenario	baseline	structure-guided
2 identical	<1s ✘	<1s ✘
2 identical + 1 fresh	>12h	2s ✘
3 identical + 1 fresh	>12h	3s ✘
2 identical + 2 fresh	>12h	1min20 ✓
2 identical + 3 fresh	>12h	11h06 ✓

✘ non-equivalent

✓ equivalent

Experimental results (1)

Unlinkability in the Electronic passport

$\overset{?}{\approx}$

✘ non-equivalent
✓ equivalent

Experimental results (2)

Vote privacy in Helios (vote swap)

$\overset{?}{\approx}$

✘ non-equivalent
✓ equivalent

DEEPSEC

v1.0.2

Experimental results (2)

Vote privacy in Helios (vote swap)

Scenario	baseline	structure-guided
no revote	<1s ✓	<1s ✓
A x 2 + B x 1	2h41 ✓	1min2 ✓
A x 3 + B x 2	>12h	7min40 ✓
A x 4 + B x 2	>12h	16min36 ✓
A x 7 + B x 3	>12h	3h53 ✓

✘ non-equivalent

✓ equivalent

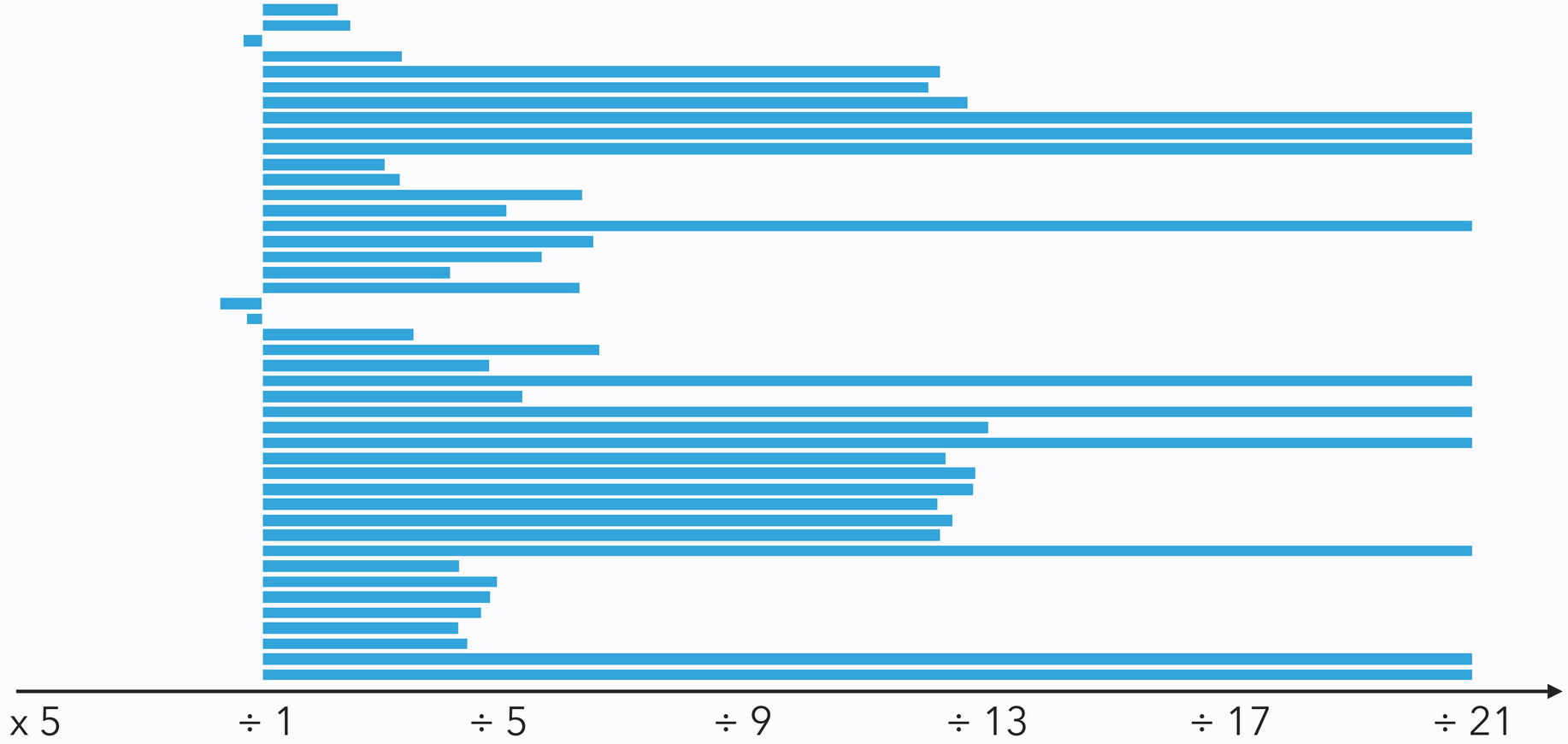
v1.0.2

~~v1.0.2~~ v2.0.0

DEEPSEC

~~v1.0.2~~ v2.0.0

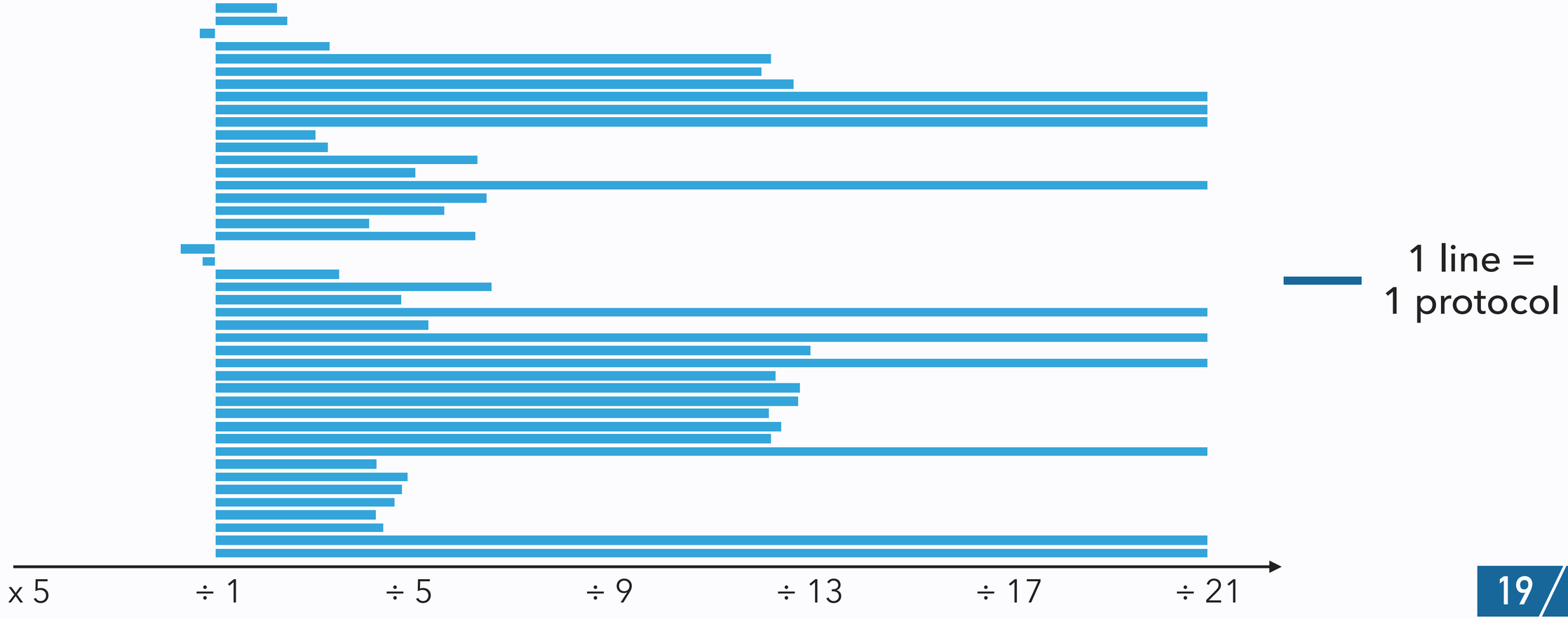
Evolution of verification time v1.0.2 → v2.0.0



DEEPSEC

~~v1.0.2~~ v2.0.0

Evolution of verification time v1.0.2 → v2.0.0



DEEPSEC

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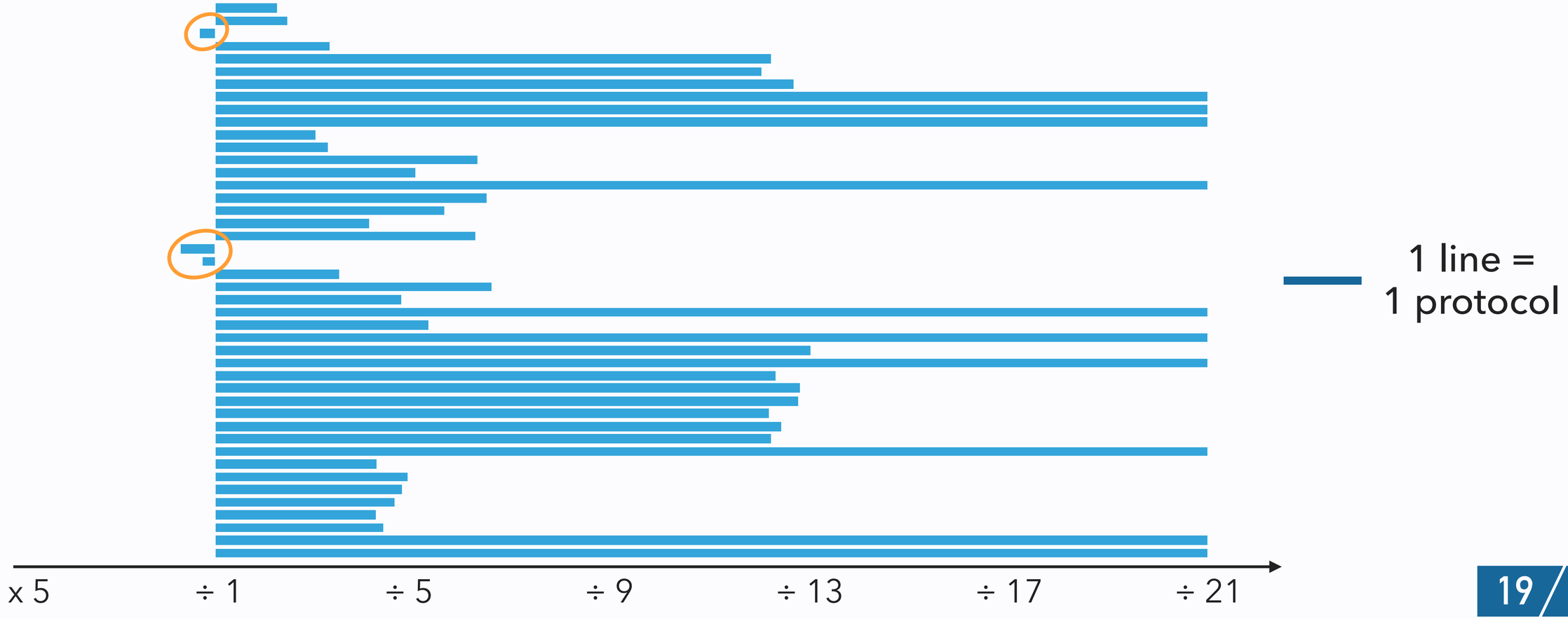

DEEPSEC

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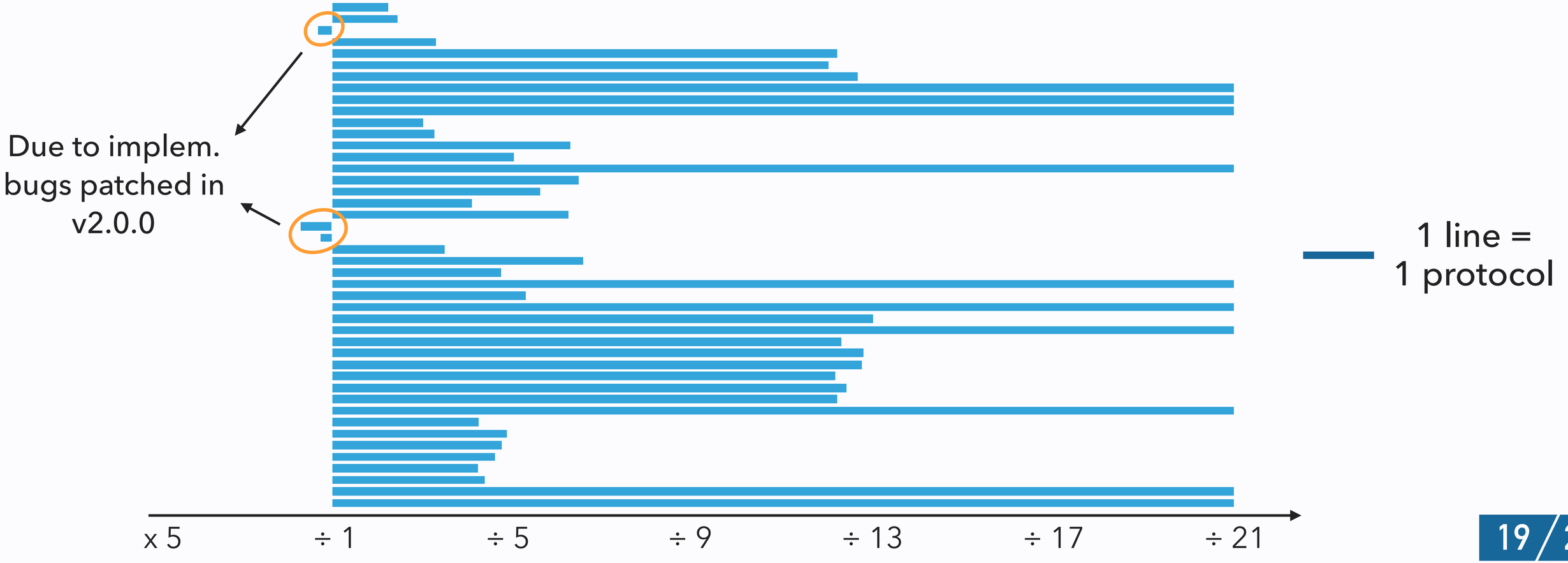

Helios_revote_ZKP21.dps Settings

```
11    free yes.
12    free no.
13
14    (* Randomized asymmetric encryption *)
15
16    fun aenc/3.
17    fun pk/1.
18
19    reduc adec(sk, aenc(pk(sk), sr, xm)) -> xm.
20
21    (* Signature *)
22
23    fun sign/2.
24    fun vk/1.
25    reduc checksign(vk(sk), sign(sk,m)) -> m.
26
```

DEEPSEC v2.0.0

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```

DEEPSEC v2.0.0

Definition of crypto primitives
(here, asymmetric encryption)

Helios_revote_ZKP21.dps Settings

```
36    fun s/1.
37
38    (* The voting process *)
39
40    let Voter(sk,id,v,pkE) =
41        new r;
42        let ballot = aenc(pkE, r, v) in
43        let zk = zkp(r, id, v, ballot) in
44        out(c, (id, sign(sk, (ballot, zk)))).
45
46    (* The Tally *)
47
48    let Outcome(prv_ch,skE) =
49      in(prv_ch,z);
50      let (vote1,vote2,vote3,nb_vote) = z in
51
```

DEEPSEC v2.0.0

Helios_revote_ZKP21.dps Settings

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DEEPSEC v2.0.0

Definition of the protocol (here, voting process)

Helios_revote_ZKP21.dps Settings

```
93      out(c,pk(skE));
94      new sk1;
95      new sk2;
96      new sk3;
97      out(c,sk3);
98      out(c,vk(sk1));
99      out(c,vk(sk2)); (
100       !^2 Voter(sk1,id1,vote1,pk(skE)) |
101       Voter(sk2,id2,vote2,pk(skE)) |
102       Tally(skE,vk(sk1),vk(sk2),vk(sk3))
103     ).
104
105   (* Should not find an attack. *)
106   query
      session_equiv(VotingSystem21(yes,no),VotingSystem21(no,yes)).
107
```

DEEPSEC v2.0.0

Helios_revote_ZKP21.dps Settings

```
93      out(c,pk(skE));
94      new sk1;
95      new sk2;
96      new sk3;
97      out(c,sk3);
98      out(c,vk(sk1));
99      out(c,vk(sk2)); (
100       !^2 Voter(sk1,id1,vote1,pk(skE)) |
101       Voter(sk2,id2,vote2,pk(skE)) |
102       Tally(skE,vk(sk1),vk(sk2),vk(sk3))
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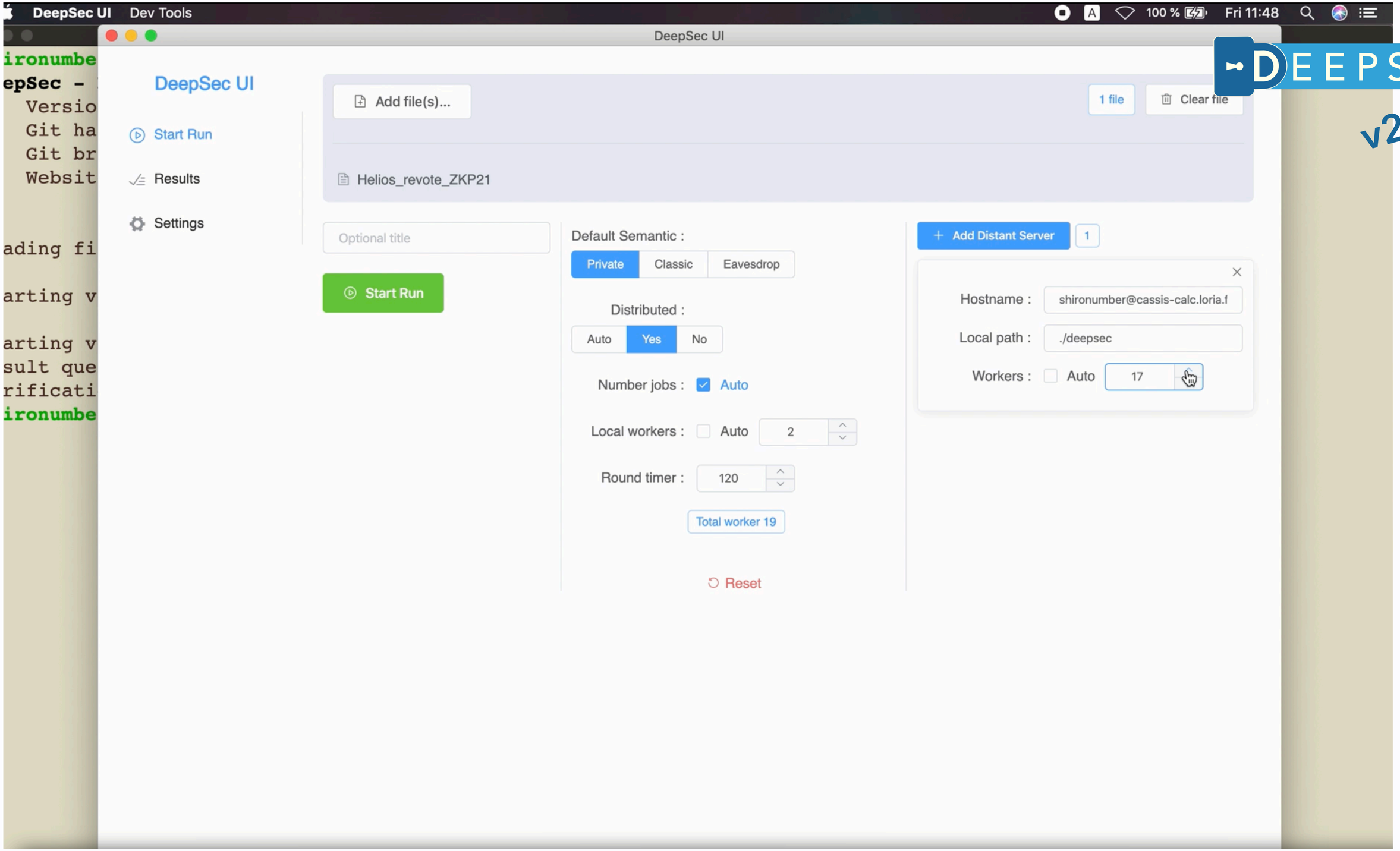
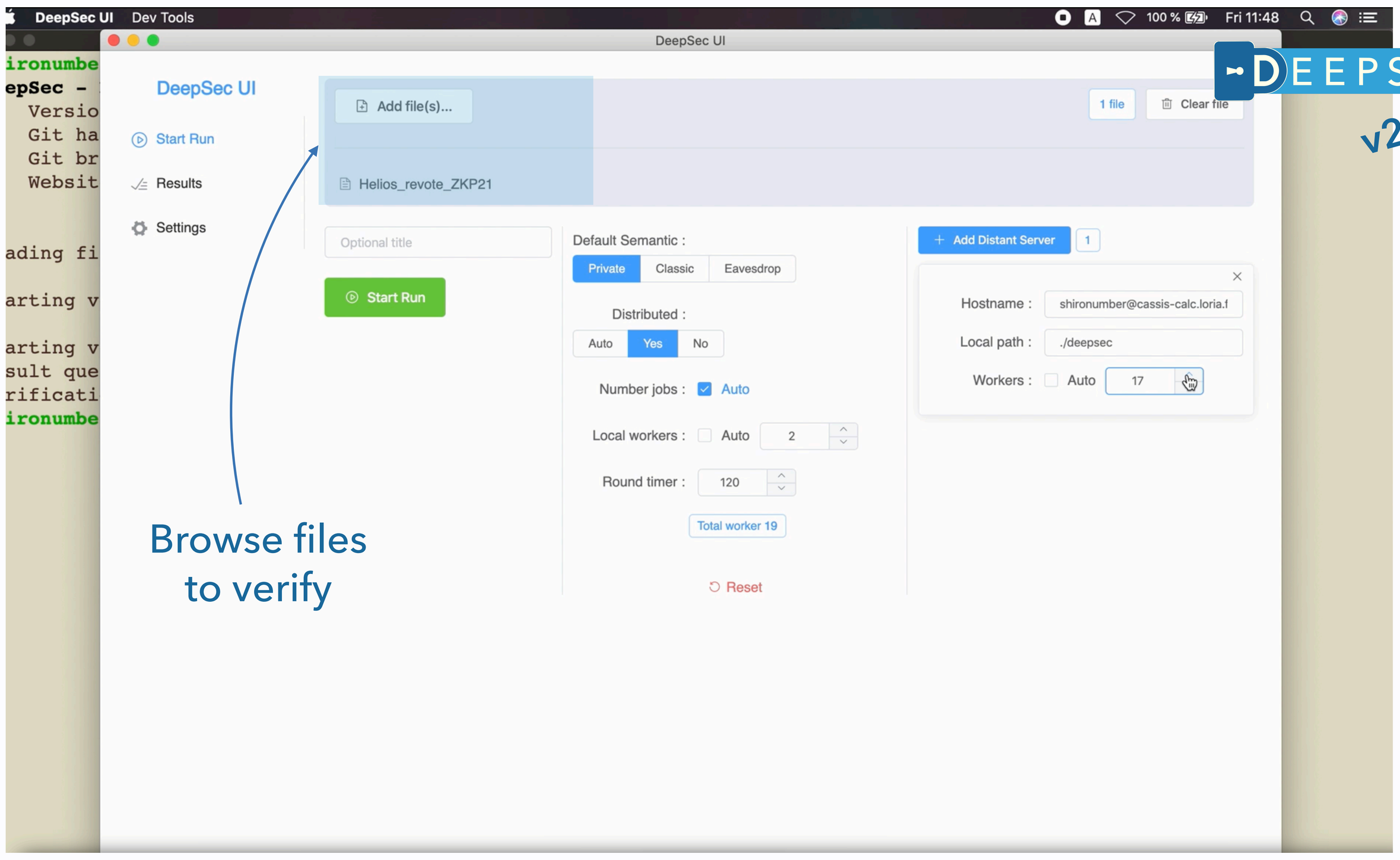
DEEPSEC v2.0.0

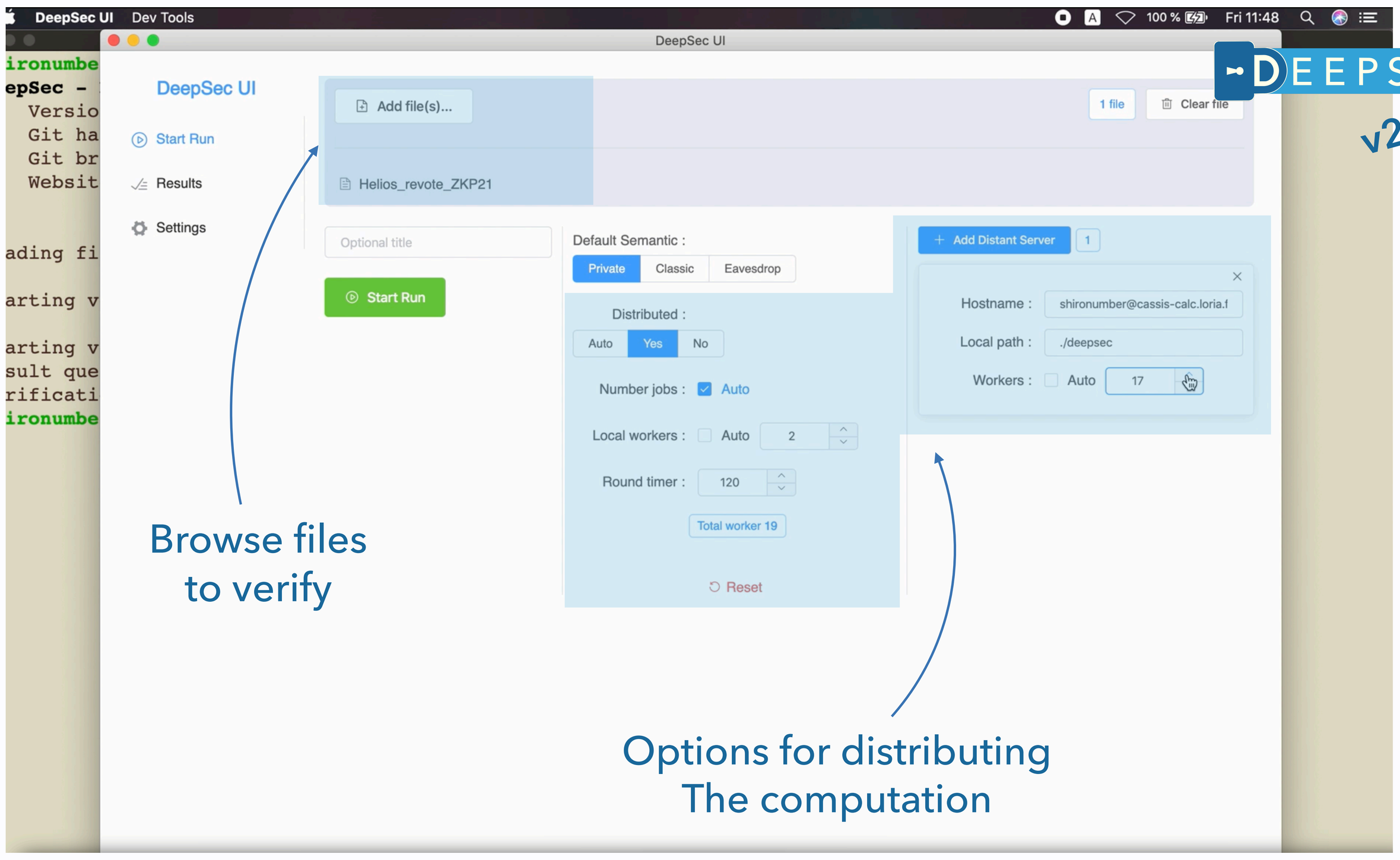
Equivalence query (here: model of vote privacy)



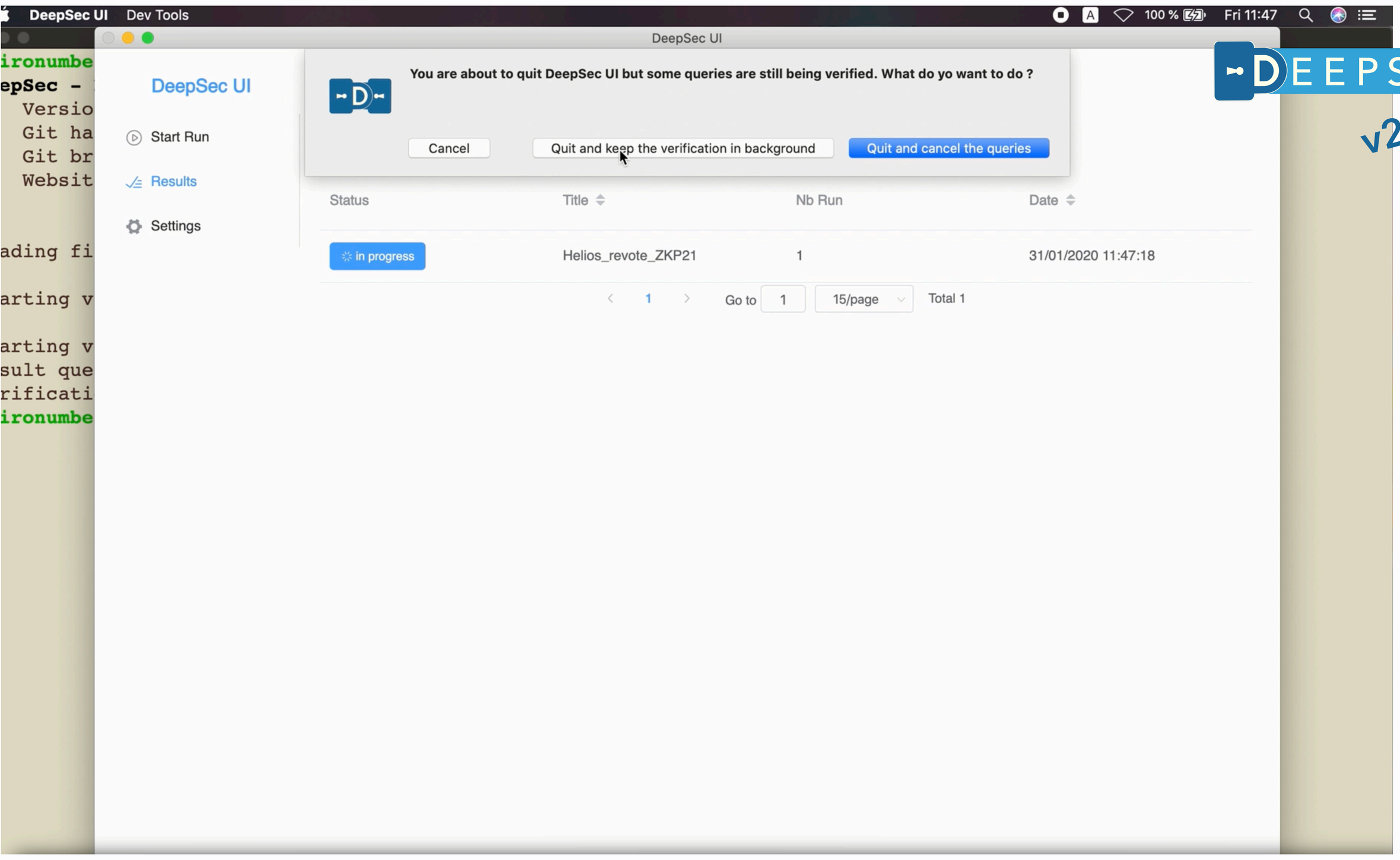
DEEPSEC
v2.0.0



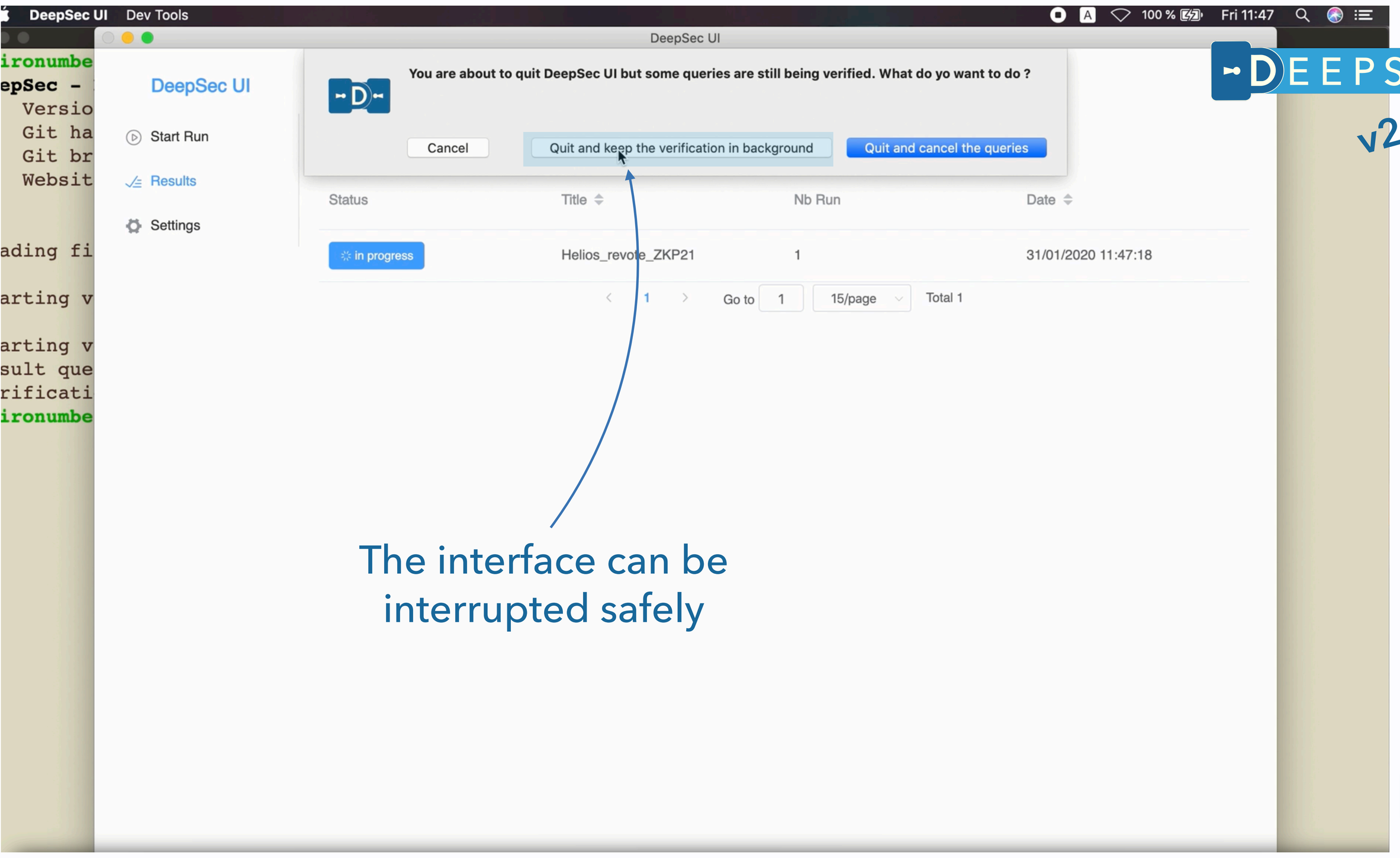
DEEPSEC
v2.0.0



DEEPSEC
v2.0.0



DEEPSEC
v2.0.0



The interface can be interrupted safely

DEEPSEC v2.0.0

DeepSec UI Dev Tools

DeepSec UI

DEEPSEC v2.0.0

Attack on Process 2

```
1  (
2     in(mn,x1);
3     in(mn,x2);
4     in(mn,x3);
5     (
6        out(ch,adec(x3,skT))
7     ) | (
8        out(ch,adec(x1,skT))
9     ) | (
10       out(ch,adec(x2,skT))
11    )
12 ) | (
13    out(ch,(a,aenc(no,r,pk(skT))))
14 ) | (
15    new r2;
16    let ballot2 = aenc(yes,r2,pk(skT)) in
17    out(bb,(b,ballot2));
18    out(ch,(b,ballot2))
19 ) | (
20    in(ch,b3);
21    let (=c,v3) = b3 in
22    out(mn,v3)
23 ) | (
24    let (=a,v1) = (a,aenc(no,r,pk(skT))) in
25    out(mn,v1)
26 ) | (
27    in(bb,b2);
28    let (=b,v2) = b2 in
29    out(mn,v2)
30 )
```

Default | I/O | All

« ‹ Prev Next › »

Trace - Step 8 / 21

5 - out(ch,ax_1)
8 - τ internal communication
9 - out(ch,ax_2)

Frame

Private names: bb, r, mn, skT

ax_1 -> pk(skT)

DeepSec UI Dev Tools

DeepSec UI

DEEPSEC v2.0.0

Attack on Process 2

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25    out(mn,v1)
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27    in(bb,b2);
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```

Default | I/O | All

« | ‹ Prev | Next › | »

Trace - Step 8 / 21

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Frame

Private names: bb, r, mn, skT

ax_1 -> pk(skT)

When query finished: result dynamically displayable (here: attack trace)

Conclusion

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- ⊕ A new equivalence exploiting the structure of practical privacy statements
- ⊕ Decision of trace equivalence improved by orders of magnitude on concrete examples
- ➡ Future work: Complete procedure for trace equivalence guided by equivalence by session