A Labeled Logic for Analyzing Cyber-Forensics Evidence

Luca Viganò

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Agenda

The Future is Interconnected

- *In 2020 there is an expectation of more than 20 billions of IoT devices connected* (McAfee labs)
- The growing of connectivity increases the security challenges
- *"Every minute, we are seeing about half a million attack attempts that are happening in Cyber Space"*(Fortinet)
- The cost of Cyber Crime Damage by 2021 will reach $6 Trillion (Cybersecurity Ventures)

The Problem

- Forensics investigations often produce an enormous amount of evidence
  - Pieces of evidence are produced/collected by various sources:
    - humans (e.g., another analyst) or
    - forensic tools such as intrusion detection system (IDS), traceback systems, malware analysis tools, and so on.

- The forensics investigator needs to
  - collect the evidence
  - check the sources of the evidence for evaluating their reliability
  - deal with enormous amount of pieces of evidence
  - analyse incomplete and/or conflicting evidence

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  There is some confusion about the dates (1984-85 and 1990-91), so what can Erisa conclude?

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What should an analyst conclude from these discording statements and pieces of evidence?

How can a decision be made?

Our Solution

Solution

Evidence Logic $\mathcal{EL}$ and its Rewriting Procedure represent the pieces of evidence, analyse and filter them by using the relations of trust between sources and reasonings

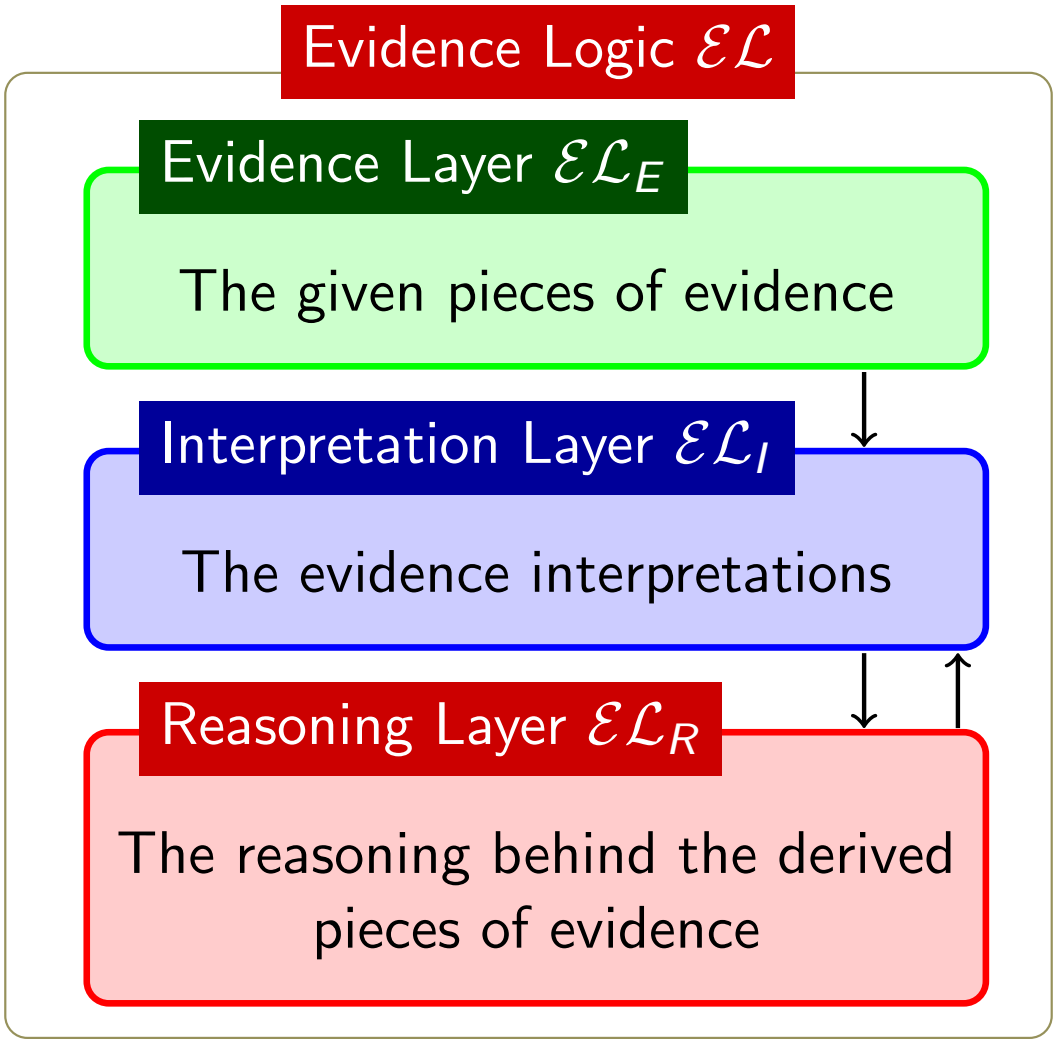
- Our solution filters the enormous amount of evidence
- Solves temporal and factual discordancies
- $\mathcal{EL}$ and the Rewriting Procedure are sound

Evidence Logic $\mathcal{EL}$

- **Evidence Logic** $\mathcal{EL}$ is based on Linear Temporal Logic and permits to represent:
  - the different pieces of evidence
  - the evidence source and sources relations of trust
  - the reasoning behind the derived pieces of evidence and their relations of trust

- In a nutshell:
  - **Evidence** represents information related to the attack, where a given (piece of) evidence usually represents an event, its occurrence and the source of the information of the occurrence of the event (another analyst, a cyber-forensics tool, etc.)
  - **Evidence interpretation** represents what the analyst thinks about the occurrence of an event e and about the occurrences of the events causing e

Evidence Logic Layers



$\mathcal{EL}_E$: Evidence

Definition

Given $t, t_1, \ldots t_n \in T$, $a, a_1, \ldots a_n \in Ag$, $r_1, r_2 \in \mathcal{R}$, $p \in Vars_S$ and $\phi, \phi_1, \ldots, \phi_n \in Lit$, the set ρ of formulas of $\mathcal{EL}_E$ is

$$\begin{aligned} \rho ::= \quad & a : (t : \phi) \mid \\ & a : (t : \phi)\ [a_1 : (t_1 : \phi_1) \mid \ldots \mid a_n : (t_n : \phi_n)]_r \mid \\ & a_1 \lhd_p a_2 \mid r_1 \prec r_2 \end{aligned}$$

$$Alice : (t : SourceAttack(A, IP_1)) \qquad Bob : (t : \neg SourceAttack(A, IP_1))$$
$$Bob \lhd_{SourceAttack} Alice$$

$$Charlie : (t : AttackOrigin(A, Area_1))\ [Alice : (t : SourceAttack(A, IP_1)) \mid Geoloc : (t : Geo(IP_1, Area_1))]_{r_1}$$

Simple Evidence and Derived Evidence

- The simple evidence expresses that the agent represented by the source label a thinks that the literal ϕ is true at the instant of time represented by the temporal label t

$$a : (t : \phi)$$

- The derived evidence expresses that a thinks that ϕ is true at instant of time t *because* of reasoning r, where a_1 thinks that ϕ_1 is true at t_1, ... and a_n thinks that ϕ_n is true at t_n

$$a : (t : \phi)\ [a_1 : (t_1 : \phi_1) \mid a_2 : (t_2 : \phi_2) \mid \ldots \mid a_n : (t_n : \phi_n)]_r$$

  - In other words, based on r, a thinks that ϕ is *caused* by $\phi_1, \cdots, \phi_n$ (with their respective time instants and agents).
  - The reasoning r of the derived evidence $a : (t : \phi)$ is composed of simple and/or derived pieces of evidence.
    We forbid cycles between derived pieces of evidence: if $a_i : (t_i : \phi_i)\ [\cdots \mid a_j : (t_j : \phi_j) \mid \ldots]_r$, then $a_j : (t_j : \phi_j)\ [\cdots \mid a_i : (t_i : \phi_i) \mid \ldots]_{r'}$ is not a wff.

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$$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$$

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$$\overbrace{CS}^{Source} : (\overbrace{t_1}^{Time} : \overbrace{Attack}^{Event}) \overbrace{[CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}}^{Simple/Derived\ Evidence\ used\ by\ r_1}$$

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$$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1} \Big\} \rightarrow \begin{array}{l} Derived \\ Evidence \end{array}$$

Other Pieces of Evidence

- TheForensicator (TF): the attack occurred the 5th of July 2016. Analysing the released metadata: physical transfer, as the created data were transferred on the speed of 23MB/s and the data were created the 5th of July 2016.

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$$\left.\begin{array}{l} TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE \end{array}\right\} \rightarrow Relational\ Formula$$

Evidence Representation with $\mathcal{EL}_E$

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
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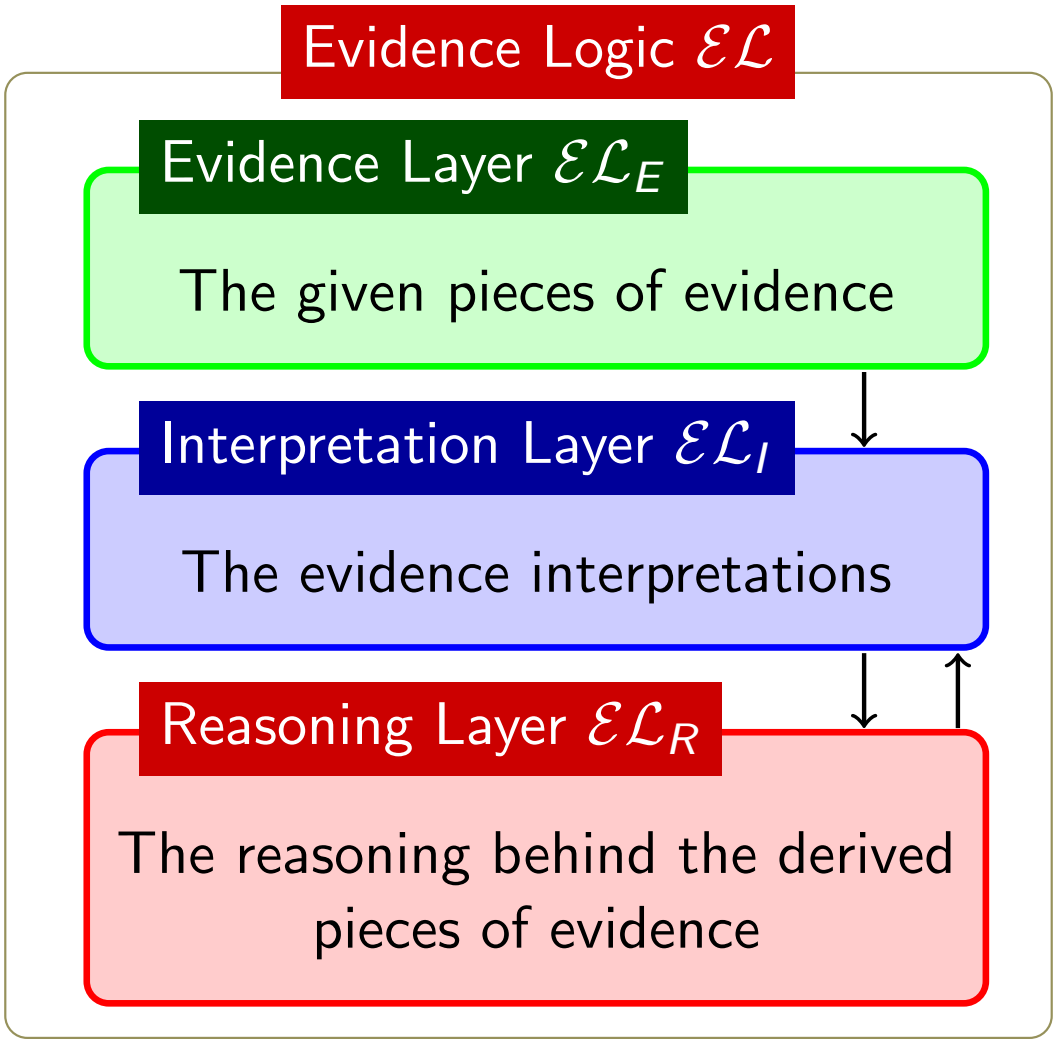
Evidence Logic Layers



$\mathcal{EL}_I$: Evidence Interpretation

- *Evidence interpretation*: what analyst thinks is plausibly true.
- Second level $\mathcal{EL}_I$ of $\mathcal{EL}$ employs a simplified variant of *LTL*.
- $\mathcal{EL}_I$ inherits from $\mathcal{EL}_E$: temporal labels T, reasonings $\mathcal{R}$ and propositional variables *Vars* (and thus also literals *Lit*).

Definition

Given $t, t_1, \ldots t_n \in T$, $\phi, \phi_1, \ldots, \phi_n \in Lit$, $r \in \mathcal{R}$ and $\phi' \in Lit_D$, the set φ of formulas of $\mathcal{EL}_I$, called interpretations, is

$$\varphi ::= \; t : \phi \mid t_1 : \phi_1 \wedge t_2 : \phi_2 \wedge \ldots \wedge t_n : \phi_n \rightarrow_r t : \phi'$$

$t_1 : \phi_1 \wedge \ldots \wedge t_n : \phi_n \rightarrow_r t : \phi'$ means analyst thinks that ϕ' is true at t, based on r, if ϕ_i is true at t_i for all $i \in \{1, \ldots, n\}$.

- Interpretation expresses a positive event $t : p$ (occurrence of event) or a negative event $t : \neg p$ (non occurrence of event).
- Interpretations that express positive events represent *plausible pieces of evidence* and help analyst perform a correct analysis.

$\mathcal{EL}_I$: Evidence Interpretation

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$t : SourceAttack(A, IP_1) \wedge t : Geo(IP_1, Area_1) \rightarrow_{r_1} t : AttackOrigin(A, Area_1)$

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$$t_1 : SpPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack \Big\} \rightarrow \text{Evidence Interpretation}$$

Evidence Interpretation with $\mathcal{EL}_I$

Evidence Layer $\mathcal{EL}_E$

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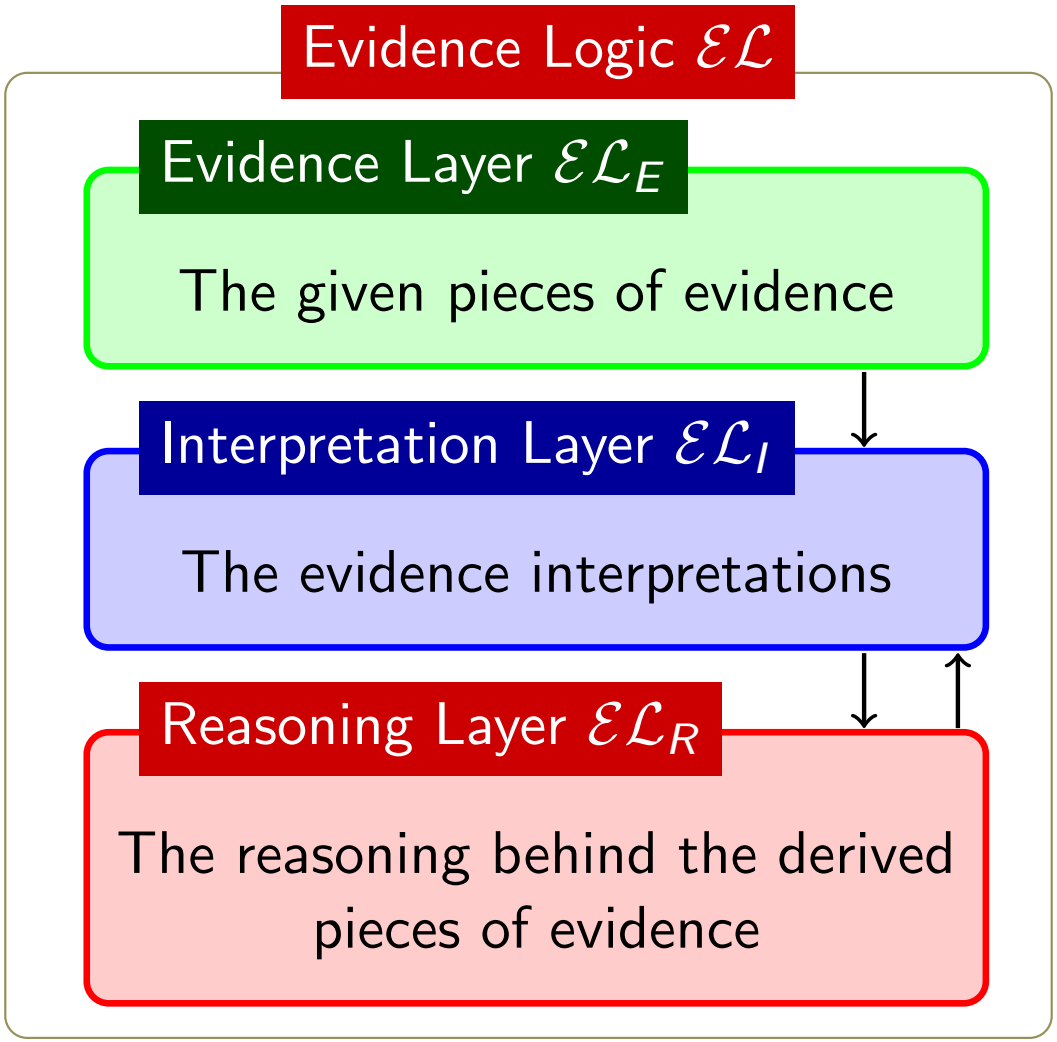
Interpretation Layer $\mathcal{EL}_I$

$t_1 : SpPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack$
$t_2 : NonPhysicalSpeedTrans(23MB/s)$

Evidence Logic Layers



Evidence Reasoning

- The third layer $\mathcal{EL}_R$ of $\mathcal{EL}$ is the *reasoning layer* and deals with the reasoning behind the derived evidence.
- Also $\mathcal{EL}_R$ uses LTL and inherits from $\mathcal{EL}_E$ temporal labels T, reasonings $\mathcal{R}$ and propositional variables *Vars*.

Definition

Given $t \in T$, $\phi \in Lit_D$ and $r, r_k, \ldots, r_l \in \mathcal{R}$, the set ψ of formulas of $\mathcal{EL}_R$ is

$$\psi ::= (t : \phi)_r \mid (t : \phi)_{r,r_k,\ldots,r_l}.$$

- The *reasoning* involves only derived pieces of evidence, which we can divide in two types (first special case of second).
- $(t : \phi)_{r,r_k,\cdots,r_l}$ composed of simple/derived pieces of evidence. The reasoning involves the one of agent stating the derived evidence, $a : (t : \phi)\ [a_1 : (t_1 : \phi_1) \mid \ldots \mid a_j : (t_j : \phi_j)]_r$, as well as all the reasonings involved in the derived pieces of evidence $\phi_i \in Lit$ for $i \in \{1, \ldots, j\}$ that are part of reasoning r.

$\mathcal{EL}_R$: Evidence Reasoning

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$$t : AttackOrigin(A, Area_1)_{r_1}$$

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Evidence Reasoning

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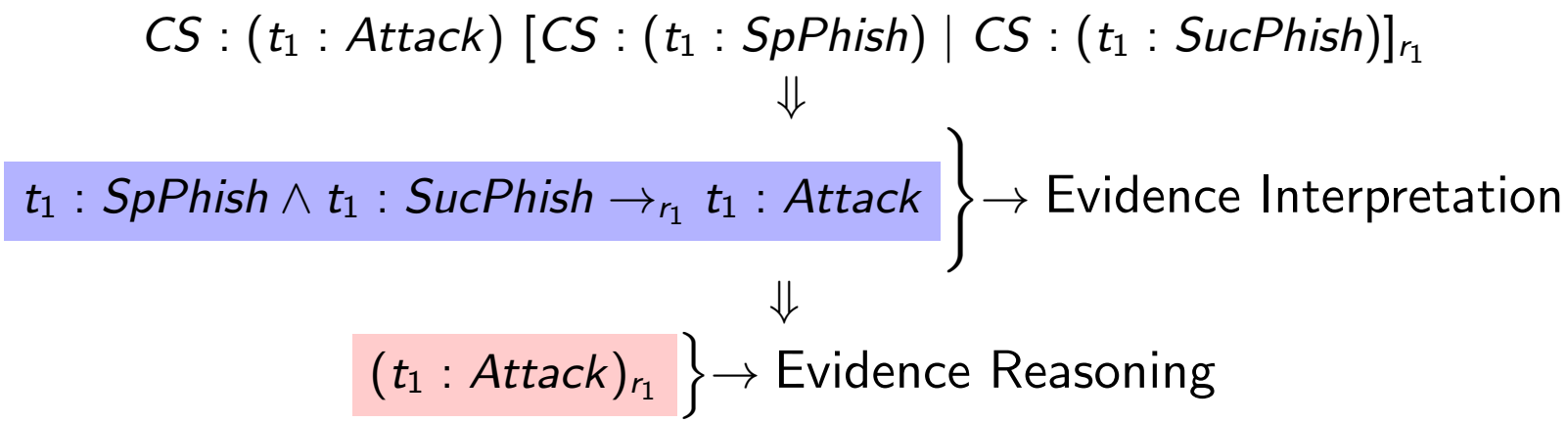
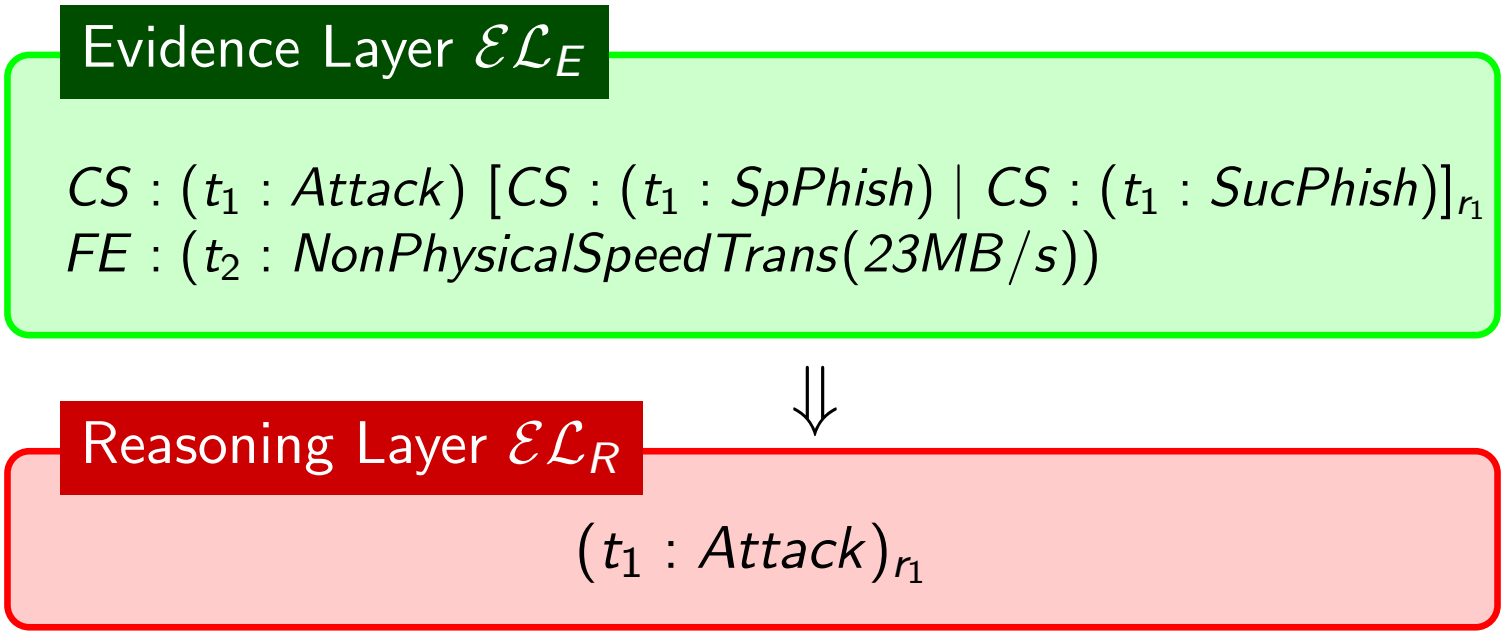
$$\Downarrow$$

$$(t_1 : Attack)_{r_1} \Big\} \rightarrow \text{Evidence Reasoning}$$

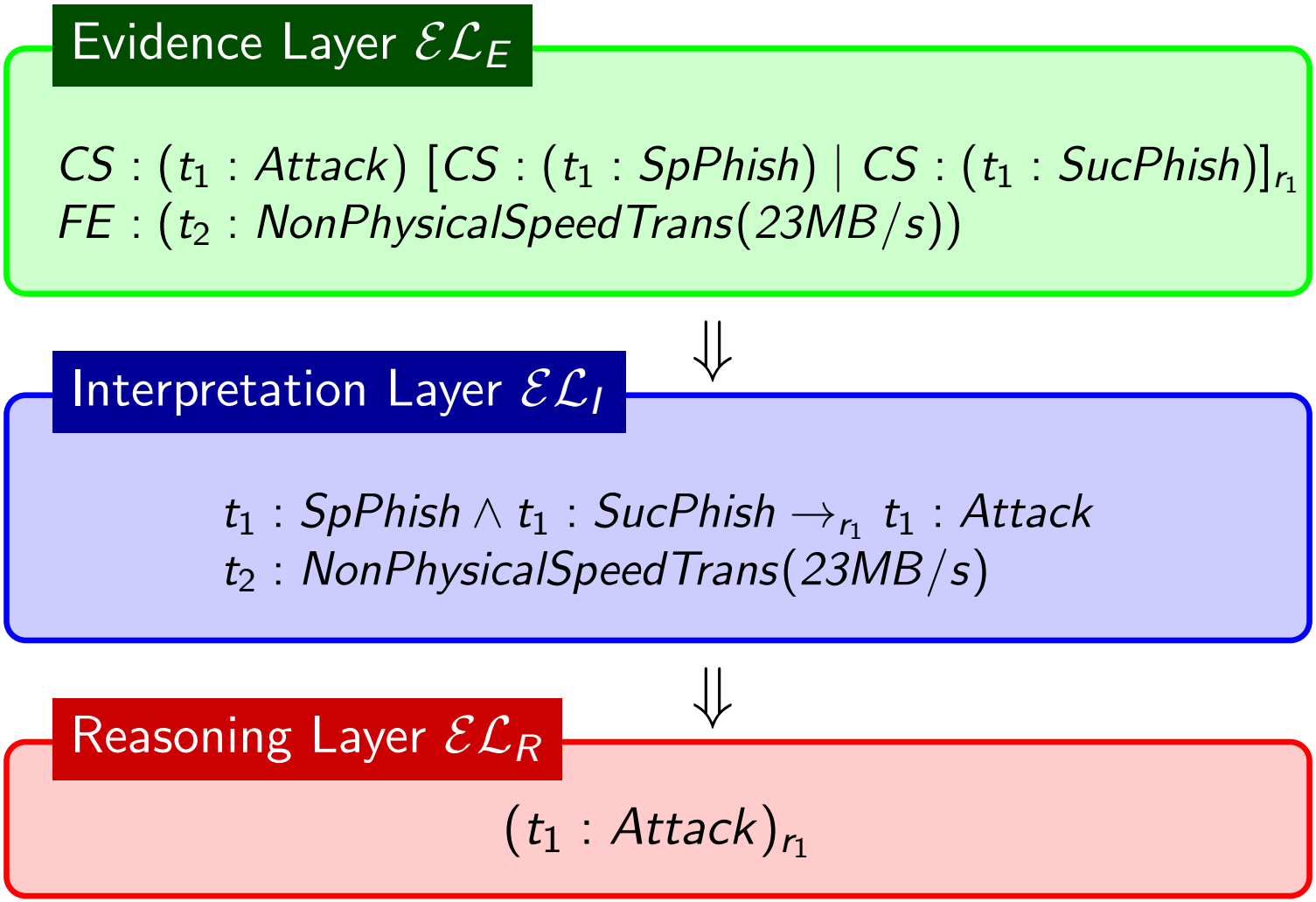
Evidence Reasoning



Evidence Reasoning with $\mathcal{EL}_R$



Evidence Reasoning with $\mathcal{EL}_R$



Semantics of $\mathcal{EL}$

Definition

The *plausible pieces of evidence* are a finite stream of temporal instants in which at every instant of time we may associate a finite number of occurrences or not occurrences of an event.

Definition

A model of the evidence language $\mathcal{EL}$ is a tuple

$$\mathfrak{M} = \{Ag^{\mathfrak{I}}, \mathcal{F}^{\mathfrak{I}}, \mathcal{PO}^{\mathfrak{I}}, \mathcal{TR}^{\mathfrak{I}}, Vars^{\mathfrak{I}}, \mathcal{R}^{\mathfrak{I}}, \mathfrak{I}\}$$

In order to avoid having clear contradictions in the models, we constrain the functions $Ag^{\mathfrak{I}}$ and $\mathcal{R}^{\mathfrak{I}}$ as follows:

- $(COND_1)$: If $a^{\mathfrak{I}}(t,p) = True$, then $a^{\mathfrak{I}}(t',p) = False$ for all $t' \neq t$.
- $(COND_2)$: If $(t,p)_{r^{\mathfrak{I}}} = True$, then $(t',p)_{r^{\mathfrak{I}}} = False$ for all $t' \neq t$.
- $(COND_3)$: Every $\lhd_p{}^{\mathfrak{I}}$ is an irreflexive and antisymmetric relation.
- $(COND_4)$: Every $\prec^{\mathfrak{I}}$ is an irreflexive and antisymmetric relation.

Rewriting System

The rewriting system gets as input the given pieces of evidence and gives as output a consistent set of pieces of evidence by

- rewriting pieces of evidence into interpretations and reasonings
- analysing the pieces of evidence
- resolving their discordances by eliminating the less trusted ones
- capturing the temporal and factual discordancies by using the trust relations

Types of Rules

- Insertion rules

$$\frac{a_1 : (t_1 : \phi) \quad a_2 : (t_2 : \phi)}{\mathcal{E} \cup \{a_1 : (t_2 : \neg\phi), a_2 : (t_1 : \neg\phi)\}} \mathcal{D}_1$$

- Elimination rules

$$\frac{a_2 \lhd_p a_1 \quad a_1 : (t : \phi) \quad a_2 : (t : \neg\phi)}{\mathcal{E} \setminus \{a_2 : (t : \neg\phi)\}} \mathcal{D}_2$$

- Closure rules

$$\frac{a : (t_1 : \phi) \quad a : (t_2 : \phi)}{\bot} \mathcal{C}_C$$

Rewriting Rules

Transformation rules

$$\frac{a : (t : \phi)}{\mathcal{E} \cup \{t : \phi\}}\ \mathcal{L}_1 \qquad \frac{(t : \phi)_{r,\cdots,r_n}}{\mathcal{E} \cup \{t : \phi\}}\ \mathcal{L}'_1$$

$$\frac{a : (t : \phi)\ [a_1 : (t_1 : \phi_1) \mid \cdots \mid a_n : (t_n : \phi_n)]_r}{\mathcal{E} \cup \{a_i : (t_i : \phi_i)\}_{\forall i \in \{1,\cdots,n\}\ \phi_i \in Lits} \cup \{t_1 : \phi_1 \wedge \cdots \wedge t_n : \phi_n \rightarrow_r t : \phi\}}\ \mathcal{L}_2$$

Rewriting Rules

Discordance resolutions rules

$$\frac{a_1 : (t_1 : \phi) \quad a_2 : (t_2 : \phi)}{\mathcal{E} \cup \{a_1 : (t_2 : \neg\phi), a_2 : (t_1 : \neg\phi)\}}\ \mathcal{D}_1 \qquad \frac{(t_1 : \phi)_{r_1} \quad (t_2 : \phi)_{r_2}}{\mathcal{E} \cup \{(t_2 : \neg\phi)_{r_1}, (t_1 : \neg\phi)_{r_2}\}}\ \mathcal{D}'_1$$

$$\frac{a_2 \lhd_p a_1 \quad a_1 : (t : \phi) \quad a_2 : (t : \neg\phi)}{\mathcal{E} \setminus \{a_2 : (t : \neg\phi)\}}\ \mathcal{D}_2 \qquad \frac{r_2 \prec r_1 \quad (t : \phi)_{r_1} \quad (t : \neg\phi)_{r_2}}{\mathcal{E} \setminus \{(t : \neg\phi)_{r_2}\}}\ \mathcal{D}'_2$$

Rewriting Rules

Transformation rules

$$\frac{a : (t : \phi)}{\mathcal{E} \cup \{t : \phi\}}\ \mathcal{L}_1 \qquad \frac{(t : \phi)_{r,\cdots,r_n}}{\mathcal{E} \cup \{t : \phi\}}\ \mathcal{L}'_1$$

$$\frac{a : (t : \phi)\ [a_1 : (t_1 : \phi_1) \mid \cdots \mid a_n : (t_n : \phi_n)]_r}{\mathcal{E} \cup \{a_i : (t_i : \phi_i)\}_{\forall i \in \{1,\cdots,n\}\ \phi_i \in Lit_S} \cup \{t_1 : \phi_1 \wedge \cdots \wedge t_n : \phi_n \rightarrow_r t : \phi\}}\ \mathcal{L}_2$$

Discordance resolutions rules

$$\frac{a_1 : (t_1 : \phi) \quad a_2 : (t_2 : \phi)}{\mathcal{E} \cup \{a_1 : (t_2 : \neg\phi), a_2 : (t_1 : \neg\phi)\}}\ \mathcal{D}_1 \qquad \frac{(t_1 : \phi)_{r_1} \quad (t_2 : \phi)_{r_2}}{\mathcal{E} \cup \{(t_2 : \neg\phi)_{r_1}, (t_1 : \neg\phi)_{r_2}\}}\ \mathcal{D}'_1$$

$$\frac{a_2 \lhd_p a_1 \quad a_1 : (t : \phi) \quad a_2 : (t : \neg\phi)}{\mathcal{E} \setminus \{a_2 : (t : \neg\phi)\}}\ \mathcal{D}_2 \qquad \frac{r_2 \prec r_1 \quad (t : \phi)_{r_1} \quad (t : \neg\phi)_{r_2}}{\mathcal{E} \setminus \{(t : \neg\phi)_{r_2}\}}\ \mathcal{D}'_2$$

Algorithm

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply $\textsc{Trans}\lhd$,$\textsc{Trans}\prec$ rules **do** Apply $\textsc{Trans}\lhd$, $\textsc{Trans}\prec$ rules **end while**
2: **while** We can apply $\textsc{Trans}\lhd$, $\textsc{Trans}\prec$ rules **do**
3: Apply $\textsc{Trans}\lhd$ and $\textsc{Trans}\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**

Rewriting Procedure

Evidence Layer $\mathcal{EL}_E$

$$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$$
$$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$
$$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$
$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$
$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Rewriting Procedure

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

- Apply rule $\mathcal{L}_2$

Transformation Rule Application

$$\frac{CS : (t_1 : Attack)\ [CS : (t_1 : SPhish) \mid CS : (t_1 : SucPhish)]_{r_1}}{\mathcal{E} \cup \{CS : (t_1 : SPhish), CS : (t_1 : SucPhish)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack\}}\ \mathcal{L}_2$$

Transformation Rule Application

$$\frac{TF : (t_2 : Attack)\ [(TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}}{\mathcal{E} \cup \{TF : (t_2 : MetaC)\} \cup \{t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack\}}\ \mathcal{L}_2$$

Transformation Rule Application

$$\frac{TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}}{\mathcal{E} \cup \{TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))\} \cup \{t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}}\ \mathcal{L}_2$$

Result of rule $\mathcal{L}_2$ application

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$
$CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : MetaC),$
$TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$

Result of rule $\mathcal{L}_2$ application and next step

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$
$CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : MetaC),$
$TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

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Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$

- Apply rule $\mathcal{D}_2$

Elimination Rule $\mathcal{D}_2$

$$\frac{TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE \quad FE : (t_2 : NonPhysicalSpeedTrans(23MB/s)) \quad TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))}{\mathcal{E} \setminus \{TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))\}}\ \mathcal{D}_2$$

Result of rule $\mathcal{D}_2$ application

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$
$CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : MetaC),$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$

Result of rule $\mathcal{D}_2$ application and next step

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$
$CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : MetaC),$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

$\Downarrow$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$

- Apply rule $\mathcal{L}_1$

Transformation Rules

$$\frac{FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))}{\mathcal{E} \cup \{t_2 : NonPhysicalSpeedTrans(23MB/s)\}}\ \mathcal{L}_1$$

$$\frac{CS : (t_1 : SPhish)}{\mathcal{E} \cup \{t_1 : SPhish\}}\ \mathcal{L}_1 \qquad \frac{CS : (t_1 : SucPhish)}{\mathcal{E} \cup \{t_1 : SucPhish\}}\ \mathcal{L}_1$$

$$\frac{TF : (t_2 : MetaC)}{\mathcal{E} \cup \{t_2 : MetaC\}}\ \mathcal{L}_1$$

Transformation Rules

$$\frac{FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))}{\mathcal{E} \cup \{t_2 : NonPhysicalSpeedTrans(23MB/s)\}}\ \mathcal{L}_1$$

$$\frac{CS : (t_1 : SPhish)}{\mathcal{E} \cup \{t_1 : SPhish\}}\ \mathcal{L}_1 \qquad \frac{CS : (t_1 : SucPhish)}{\mathcal{E} \cup \{t_1 : SucPhish\}}\ \mathcal{L}_1$$

$$\frac{TF : (t_2 : MetaC)}{\mathcal{E} \cup \{t_2 : MetaC\}}\ \mathcal{L}_1$$

Result of rule $\mathcal{L}_1$ application

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$
$t_2 : NonPhysicalSpeedTrans(23MB/s)$
$t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC$

Result of rule $\mathcal{L}_1$ application and next step

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$
$t_2 : NonPhysicalSpeedTrans(23MB/s),$
$t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC$

- Apply rule $(\rightarrow)$

Derivation of Derived Evidence

$$\frac{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack \quad t_1 : SPhish \quad t_1 : SucPhish}{\mathcal{E} \cup \{(t_1 : Attack)_{r_1}\}} \ (\rightarrow)$$

Result of rule ($\rightarrow$) application

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

$\Downarrow$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$
$t_2 : NonPhysicalSpeedTrans(23MB/s),$
$t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC$

$\Downarrow$

Reasoning Layer $\mathcal{EL}_R$

$(t_1 : Attack)_{r_1}$

Result of rule $(\rightarrow)$ application and next step

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

$\Downarrow$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$
$t_2 : NonPhysicalSpeedTrans(23MB/s),$
$t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC$

$\Downarrow$

Reasoning Layer $\mathcal{EL}_R$

$(t_1 : Attack)_{r_1}$

- Apply rule $(\mathcal{L}'_1)$

Application of rule $\mathcal{L}'_1$

$$\frac{(t_1 : Attack)_{r_1}}{\mathcal{E} \cup \{(t_1 : Attack)\}} \mathcal{L}'_1$$

Result of the rewriting procedure

Evidence Layer $\mathcal{EL}_E$

$CS : (t_1 : Attack)\ [CS : (t_1 : SpPhish) \mid CS : (t_1 : SucPhish)]_{r_1}$
$TF : (t_2 : Attack)\ [TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$
$TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$
$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$
$t_2 : NonPhysicalSpeedTrans(23MB/s),$
$t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC$
$t_1 : Attack$

Reasoning Layer $\mathcal{EL}_R$

$(t_1 : Attack)_{r_1}$

Result of the rewriting procedure

- The forensics analyst has as result the following consistent set of pieces of evidence:

Interpretation Layer $\mathcal{EL}_I$

$t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,$
$t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,$
$t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA$
$t_2 : NonPhysicalSpeedTrans(23MB/s),$
$t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC$
$t_1 : Attack$

- $\mathcal{EL}$ Logic allows us to conclude that the *Attack* occurred at the instant of time t_1 (March-April 2016)

Conclusions

- We presented a formal representation for the pieces of evidence
- Our $\mathcal{EL}$ Logic captures the evidence source, reasoning and their level of trust
- We introduced a rewriting procedure that given the pieces of evidence:
  - Captures and solves factual and temporal discordancies
  - Gives a consistent set of pieces of evidence filtered using the relations of trust

Future Work

- Implementation and testing of the framework
- Enrichment with a reputation/belief revision process
- Integration of the framework with a trust reinforcement system
- Use Bayesian belief networks
- Work with probabilities for the pieces of evidence
- Incorporate within an Attribution Process

5 Algorithm Application

Algorithm Application

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply TRANS$\lhd$,TRANS $\prec$ rules **do** Apply TRANS$\lhd$, TRANS $\prec$ rules **end while**
2: **while** We can apply TRANS$\lhd$, TRANS $\prec$ rules **do**
3: Apply TRANS$\lhd$ and TRANS $\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Algorithm Application

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply TRANS$\lhd$,TRANS $\prec$ rules **do** Apply TRANS$\lhd$, TRANS $\prec$ rules **end while**
2: **while** We can apply TRANS$\lhd$, TRANS $\prec$ rules **do**
3: Apply TRANS$\lhd$ and TRANS $\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Transformation Rule Application

$$\frac{CS : (t_1 : Attack)\ [CS : (t_1 : SPhish) \mid CS : (t_1 : SucPhish)]_{r_1}}{\mathcal{E} \cup \{CS : (t_1 : SPhish), CS : (t_1 : SucPhish)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack\}}\ \mathcal{L}_2$$

$$\frac{TF : (t_2 : Attack)\ [(TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}}{\mathcal{E} \cup \{TF : (t_2 : MetaC)\} \cup \{t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack\}}\ \mathcal{L}_2$$

$$\frac{TF : (t_2 : PhysA)\ [TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}}{\mathcal{E} \cup \{TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))\} \cup \{t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}}\ \mathcal{L}_2$$

Algorithm Application II

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply TRANS$\lhd$,TRANS $\prec$ rules **do** Apply TRANS$\lhd$, TRANS $\prec$ rules **end while**
2: **while** We can apply TRANS$\lhd$, TRANS $\prec$ rules **do**
3: Apply TRANS$\lhd$ and TRANS $\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$\mathcal{E} \cup \{CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s)),\ TF : (t_2 : MetaC)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhis \rightarrow_{r_1} t_1 : Attack,\ t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,\ t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$$

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Algorithm Application II

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply TRANS$\lhd$,TRANS $\prec$ rules **do** Apply TRANS$\lhd$, TRANS $\prec$ rules **end while**
2: **while** We can apply TRANS$\lhd$, TRANS $\prec$ rules **do**
3: Apply TRANS$\lhd$ and TRANS $\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$\mathcal{E} \cup \{CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s)),\ TF : (t_2 : MetaC)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhis \rightarrow_{r_1} t_1 : Attack,\ t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,\ t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$$

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Elimination Rule $\mathcal{D}_2$

$$\frac{TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE \quad FE : (t_2 : NonPhysicalSpeedTrans(23MB/s)) \quad TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))}{\mathcal{E} \setminus \{TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))\}}\ \mathcal{D}_2$$

Algorithm Application III

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply $\text{TRANS}\lhd$,$\text{TRANS}\prec$ rules **do** Apply $\text{TRANS}\lhd$, $\text{TRANS}\prec$ rules **end while**
2: **while** We can apply $\text{TRANS}\lhd$, $\text{TRANS}\prec$ rules **do**
3: Apply $\text{TRANS}\lhd$ and $\text{TRANS}\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$\mathcal{E} \cup \{CS : (t_1 : SPhish),\ CS : (t_1 : SucPhish),\ TF : (t_2 : MetaC)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,\ t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,\ t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$$

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Transformation Rule

$$\frac{FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))}{\mathcal{E} \cup \{t_2 : NonPhysicalSpeedTrans(23MB/s)\}}\ \mathcal{L}_1$$

$$\frac{CS : (t_1 : SPhish)}{\mathcal{E} \cup \{t_1 : SPhish\}}\ \mathcal{L}_1 \qquad \frac{CS : (t_1 : SucPhish)}{\mathcal{E} \cup \{t_1 : SucPhish\}}\ \mathcal{L}_1$$

$$\frac{TF : (t_2 : MetaC)}{\mathcal{E} \cup \{t_2 : MetaC\}}\ \mathcal{L}_1$$

Algorithm Application IV

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply $\textsc{Trans}\lhd$,$\textsc{Trans}\prec$ rules **do** Apply $\textsc{Trans}\lhd$, $\textsc{Trans}\prec$ rules **end while**
2: **while** We can apply $\textsc{Trans}\lhd$, $\textsc{Trans}\prec$ rules **do**
3: Apply $\textsc{Trans}\lhd$ and $\textsc{Trans}\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\bot$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$\mathcal{E} \cup \{t_1 : SPhish,\ t_1 : SucPhish, t_2 : MetaC, t_2 : NonPhysicalSpeedTrans(23MB/s)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack, t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack, t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$$

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Algorithm Application IV

Algorithm 1 Algorithm for the Rewriting Procedure

1: **while** We can apply TRANS$\lhd$,TRANS $\prec$ rules **do** Apply TRANS$\lhd$, TRANS $\prec$ rules **end while**
2: **while** We can apply TRANS$\lhd$, TRANS $\prec$ rules **do**
3: Apply TRANS$\lhd$ and TRANS $\prec$ rules
4: **end while**
5: Apply $\mathcal{C}_T$ and $\mathcal{C}'_T$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
6: **while** We can apply $\mathcal{L}_2$ rule **do** Apply $\mathcal{L}_2$ rule **end while**
7: **while** We can apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **do** Apply $\mathcal{D}_1$, $\mathcal{D}_2$ rules **end while**
8: Apply $\mathcal{C}_C$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
9: **while** We can apply $\mathcal{L}_1$ rule **do** Apply $\mathcal{L}_1$ rule **end while**
10: **while** We can apply $(\rightarrow)$ rule **do** Apply $(\rightarrow)$ rule **end while**
11: **while** We can apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **do** Apply $\mathcal{D}'_1$, $\mathcal{D}'_2$ rules **end while**
12: **while** We can apply $(\rightarrow')$ rule **do** Apply $(\rightarrow')$ rule **end while**
13: **while** We can apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **do** Apply $\mathcal{D}''_1$, $\mathcal{D}''_2$ rules **end while**
14: Apply $\mathcal{C}'_C$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**
15: **while** We can apply $\mathcal{L}'_1$ rule **do** Apply $\mathcal{L}'_1$ rule **end while**
16: Apply $\mathcal{C}_P$; **if** we have $\perp$, **then** We do not have a model. Exit! **endif**

Pieces of Evidence

$$\mathcal{E} \cup \{t_1 : SPhish,\ t_1 : SucPhish,\ t_2 : MetaC,\ t_2 : NonPhysicalSpeedTrans(23MB/s)\} \cup \{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack,\ t_2 : MetaC \wedge t_2 : PhysA \rightarrow_{r_2} t_2 : Attack,\ t_2 : \neg NonPhysicalSpeedTrans(23MB/s) \rightarrow_{r_3} t_2 : PhysA\}$$

$$CS : (t_1 : Attack)[CS : (t_1 : SpPhish) \mid CS : (t_1 : (SucPhish)]_{r_1}$$

$$TF : (t_2 : Attack)[TF : (t_2 : MetaC) \mid TF : (t_2 : PhysA)]_{r_2}$$

$$TF : (t_2 : PhysA)[TF : (t_2 : \neg NonPhysicalSpeedTrans(23MB/s))]_{r_3}$$

$$FE : (t_2 : NonPhysicalSpeedTrans(23MB/s))$$

$$TF \lhd_{NonPhysicalSpeedTrans(23MB/s)} FE$$

Derivation of Derived Evidence

$$\frac{t_1 : SPhish \wedge t_1 : SucPhish \rightarrow_{r_1} t_1 : Attack \quad t_1 : SPhish \quad t_1 : SucPhish}{\mathcal{E} \cup \{(t_1 : Attack)_{r_1}\}} (\rightarrow)$$

$$\Downarrow$$

$$\frac{(t_1 : Attack)_{r_1}}{\mathcal{E} \cup \{(t_1 : Attack)\}} \mathcal{L}'_1$$