The Attacker Does not Always Hold the Initiative:

Attack Trees with External Refinement

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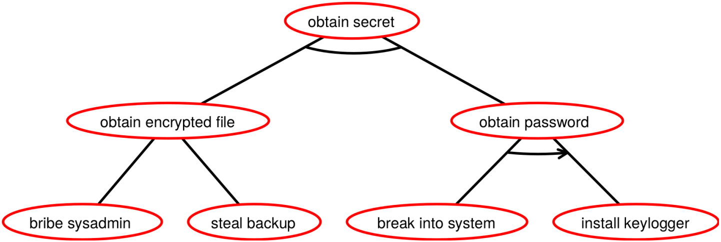
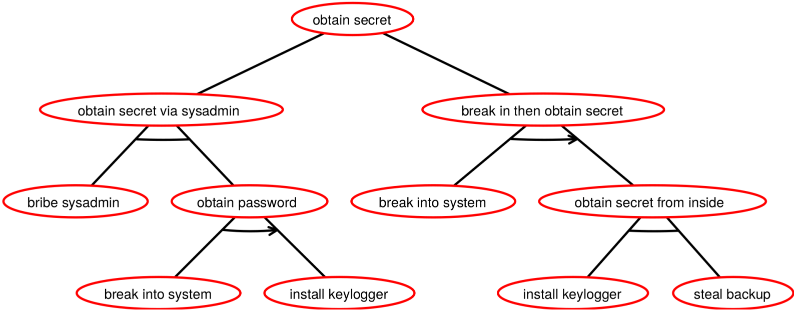
Background: Causal Attack Trees



Three types of refinement:

- Node with undirected arc represents *conjunctive refinement*.
- Node with no arc represents *disjunctive refinement*.
- Node with directed arc represents *sequential refinement*.

Attack Trees Evolve as Domain Knowledge is Specialised



In this specialised tree, “steal backup” can only be performed after breaking into the system.

Criterion for Specialisation of Attack Trees

Criterion:

A **specialisation** between attack tree is **sound** with respect to an **attribute domain** whenever:

valuations are **correlated**, for any assignment of values to basic actions.

Notes:

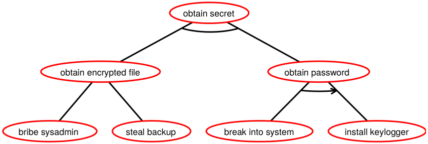
- “specialisation” and “correlation” have many interpretations.
- more general than equality.

Example: Minimum Attack Time Attribute Domain

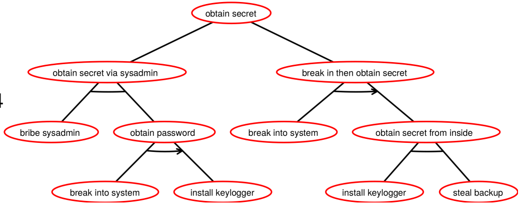
Basic minimum attack times:

bribe sysadmin $\mapsto 25$ steal backup $\mapsto 5$ break into system $\mapsto 9$ install keylogger $\mapsto 2$

$\max\{\min\{25,5\},9+2\} = 11$



$\min\{\max\{25,9+2\},9+\max\{2,5\}\} = 14$



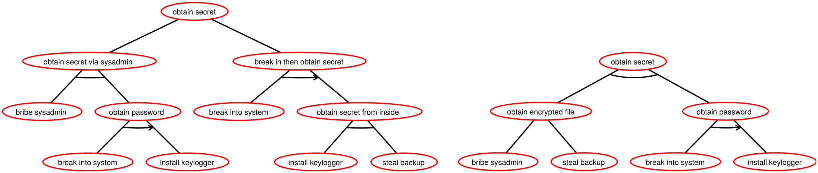
How do we know: first $\leq$ second for all assignments?

- Even for small examples, *time consuming* and *error-prone* to judge specialisations.
- Unclear what “specialisation” means.
- Better to have tool to check automatically to assist with attack tree manipulation.

Solution: define a sound **semantics** with a **decidable** specialisation relation.

Example Verified using the Calculus of Structures

The first tree specialises (implies) the second.



Proof:

$$\frac{\overline{}}{\mathrm{I}}\ \textit{axiom}$$

$$\frac{\mathrm{I}}{\mathrm{I}\ \&\ \mathrm{I}}\ \textit{tidy}$$

interaction

$$\left(\left(\overline{\textit{bribe}} \parallel \textit{bribe}\right) \otimes \left(\left(\overline{\textit{breakin}} \parallel \textit{breakin}\right) ; \left(\overline{\textit{install}} \parallel \textit{install}\right)\right)\right) \,\&\, \left(\left(\overline{\textit{breakin}} \parallel \textit{breakin}\right) ; \left(\left(\overline{\textit{steal}} \parallel \textit{steal}\right) \otimes \left(\overline{\textit{install}} \parallel \textit{install}\right)\right)\right)$$

switch

$$\left(\left(\overline{\textit{bribe}} \parallel \textit{bribe}\right) \otimes \left(\left(\overline{\textit{breakin}} \parallel \textit{breakin}\right) ; \left(\overline{\textit{install}} \parallel \textit{install}\right)\right)\right) \,\&\, \left(\left(\overline{\textit{breakin}} \parallel \textit{breakin}\right) ; \left(\left(\overline{\textit{steal}} \otimes \overline{\textit{install}}\right) \parallel \textit{steal} \parallel \textit{install}\right)\right)$$

sequence

$$\left(\left(\overline{\textit{bribe}} \parallel \textit{bribe}\right) \otimes \left(\left(\overline{\textit{breakin}} ; \overline{\textit{install}}\right) \parallel \left(\textit{breakin} ; \textit{install}\right)\right)\right) \,\&\, \left(\left(\overline{\textit{breakin}} ; \left(\overline{\textit{steal}} \otimes \overline{\textit{install}}\right)\right) \parallel \textit{steal} \parallel \left(\textit{breakin} ; \textit{install}\right)\right)$$

switch

$$\left(\left(\overline{\textit{bribe}} \otimes \left(\overline{\textit{breakin}} ; \overline{\textit{install}}\right)\right) \parallel \textit{bribe} \parallel \left(\textit{breakin} ; \textit{install}\right)\right) \,\&\, \left(\left(\overline{\textit{breakin}} ; \left(\overline{\textit{steal}} \otimes \overline{\textit{install}}\right)\right) \parallel \textit{steal} \parallel \left(\textit{breakin} ; \textit{install}\right)\right)$$

choice

$$\left(\left(\overline{\textit{bribe}} \otimes \left(\overline{\textit{breakin}} ; \overline{\textit{install}}\right)\right) \parallel \left(\textit{bribe} \oplus \textit{steal}\right) \parallel \left(\textit{breakin} ; \textit{install}\right)\right) \,\&\, \left(\left(\overline{\textit{breakin}} ; \left(\overline{\textit{steal}} \otimes \overline{\textit{install}}\right)\right) \parallel \left(\textit{bribe} \oplus \textit{steal}\right) \parallel \left(\textit{breakin} ; \textit{install}\right)\right)$$

external

$$\left(\left(\overline{\textit{bribe}} \otimes \left(\overline{\textit{breakin}} ; \overline{\textit{install}}\right)\right) \,\&\, \left(\overline{\textit{breakin}} ; \left(\overline{\textit{steal}} \otimes \overline{\textit{install}}\right)\right)\right) \parallel \left(\textit{bribe} \oplus \textit{steal}\right) \parallel \left(\textit{breakin} ; \textit{install}\right)$$

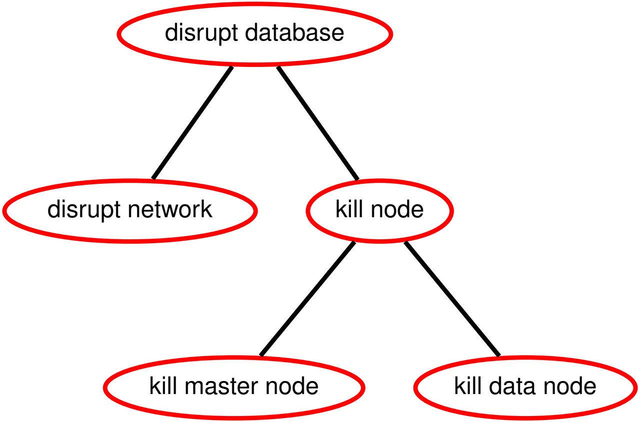
definition

$$\left(\textit{bribe} \parallel \left(\textit{breakin} ; \textit{install}\right)\right) \oplus \left(\textit{breakin} ; \left(\textit{steal} \parallel \textit{install}\right)\right) \multimap \left(\textit{bribe} \oplus \textit{steal}\right) \parallel \left(\textit{breakin} ; \textit{install}\right)$$

Breaking Asymmetry between the Attacker and its Environment

Does the attacker always have control of choices made during an attack?

E.g. Can the attacker actively chose whether it is killing a master node or data node?



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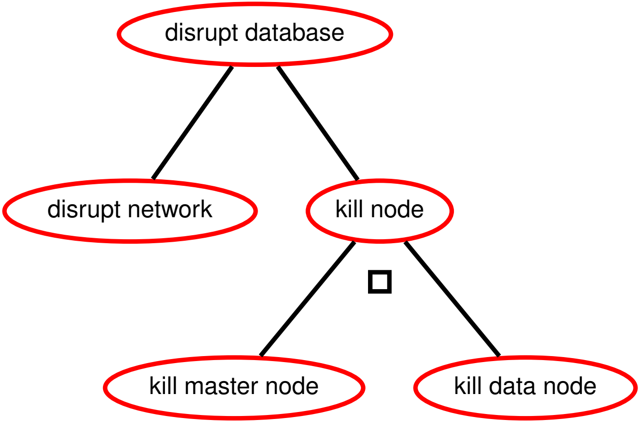
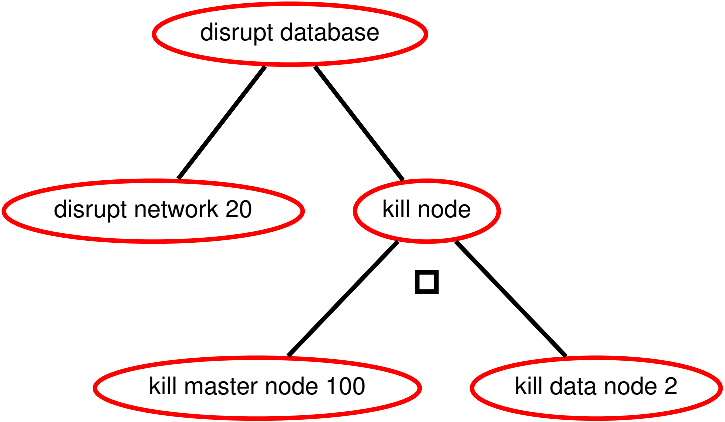
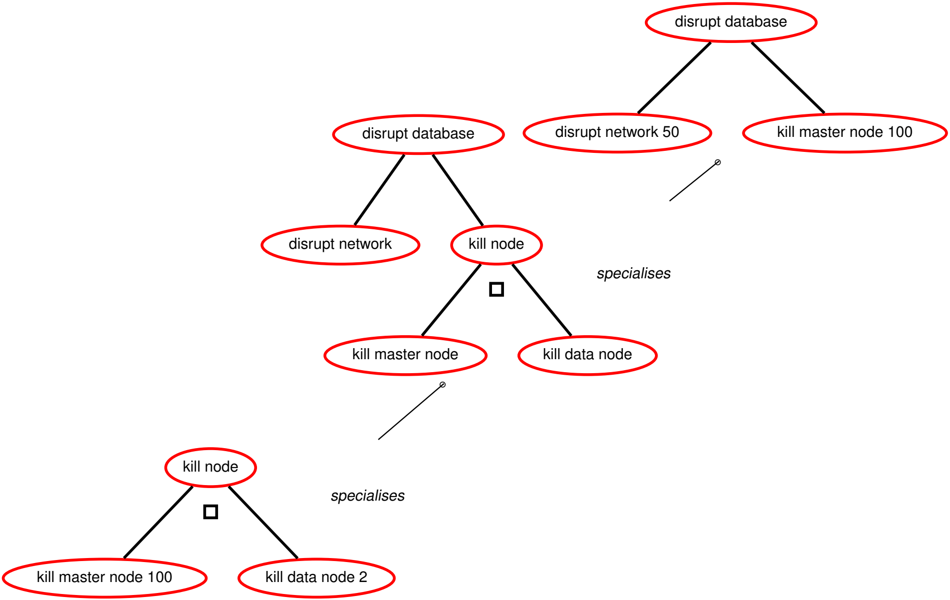


Impact of External Refinement on Quantative Analysis: Max Damage

What is the optimal attack strategy?



Trees Related by Specialisation



Additive Linear Logic in the Sequent Calculus

MALL (Girard 1993):

$$\frac{}{\vdash \overline{a}, a}\ \textit{axiom} \qquad \frac{\vdash P_i, R}{\vdash P_1 \oplus P_2, R}\ \oplus,\ i \in \{1,2\} \qquad \frac{\vdash P, R \quad \vdash Q, R}{\vdash P \,\&\, Q, R}\ \& \qquad \frac{\vdash Q, P}{\vdash P, Q}\ \textit{exchange}$$

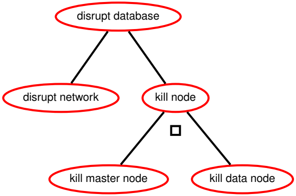
De Morgan dualities:

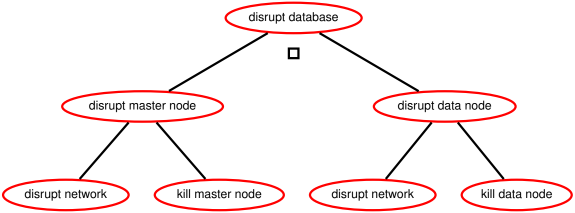
$$\overline{P \,\&\, Q} = \overline{P} \oplus \overline{Q} \qquad \overline{P \oplus Q} = \overline{P} \,\&\, \overline{Q} \qquad \overline{\overline{a}} = a$$

Linear implication ($P \multimap Q$):

$$\vdash \overline{P}, Q$$

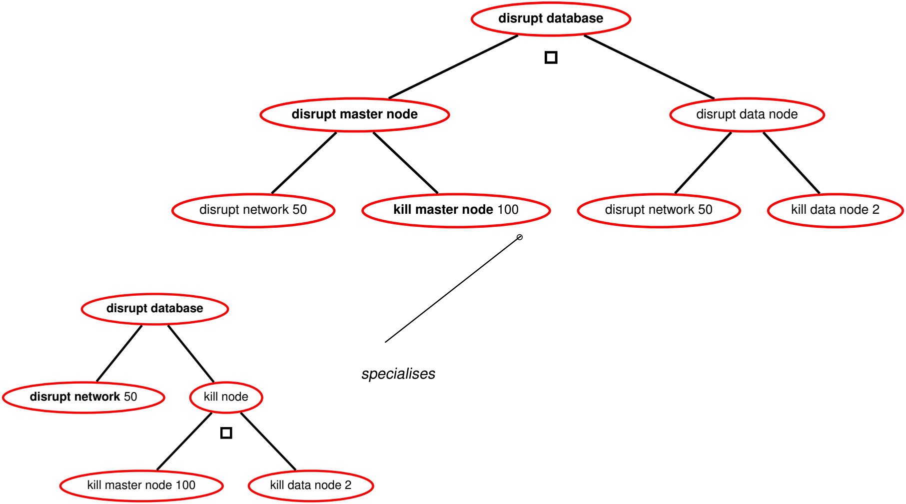
Proof of Specialisation between Attack Trees



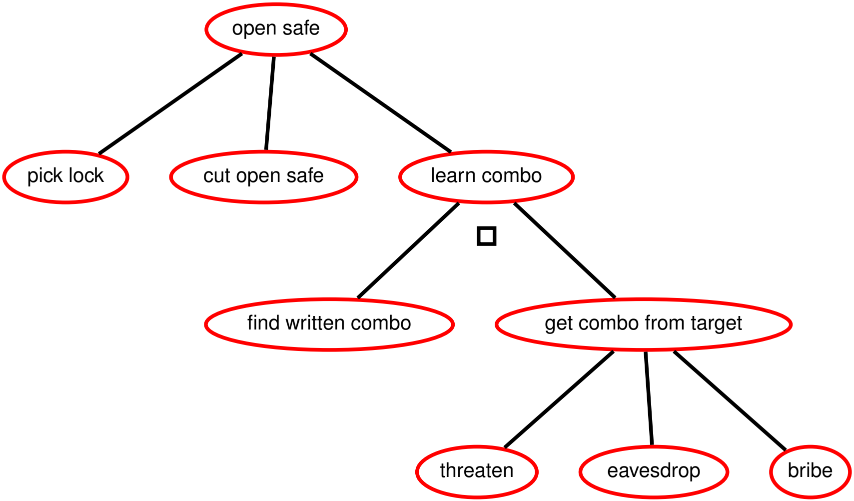


$$\dfrac{\dfrac{\dfrac{\dfrac{}{\vdash \overline{a}, a}\,axiom}{\vdash \overline{a}, a \oplus b}\,\oplus \qquad \dfrac{\dfrac{}{\vdash \overline{a}, a}\,axiom}{\vdash \overline{a}, a \oplus c}\,\oplus}{\vdash \overline{a}, (a \oplus b)\ \&\ (a \oplus c)}\,\& \qquad \dfrac{\dfrac{\dfrac{\dfrac{}{\vdash \overline{b}, b}\,axiom}{\vdash \overline{b}, a \oplus b}\,\oplus}{\vdash \overline{b} \oplus \overline{c}, a \oplus b}\,\oplus \qquad \dfrac{\dfrac{\dfrac{}{\vdash \overline{c}, c}\,axiom}{\vdash \overline{c}, a \oplus c}\,\oplus}{\vdash \overline{b} \oplus \overline{c}, a \oplus c}\,\oplus}{\vdash \overline{b} \oplus \overline{c}, (a \oplus b)\ \&\ (a \oplus c)}\,\&}{\vdash \overline{a}\ \&\ (\overline{b} \oplus \overline{c}), (a \oplus b)\ \&\ (a \oplus c)}\,\&$$

Uncertaintly in Environment and Attributes: All Strategies Preserved



Are Choices External in Schneier's Example?



Note: do not prune tree since *find writen combo* not impossible.

Conclusion

- **Specialisation** useful for comparing attack trees that are **not necessarily equal**.
- **Semantics** for each class provided by embedding in (extensions of) Linear Logic.
- Asymmetry between **Attacker** and **Environment** broken by marking *external* choices.
- Even without probabilities, specialisation is sensitive to *uncertain information*.
- . . . relevant to Moving Target Defence?