Determining an Economic Value of High Assurance for Commodity Software Security

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Outline

Why not high assurance? (~ 3 min)

Why revisit high assurance? (~ 10 min)

The need for selective high assurance (~ 10 min)

A Challenge (~ 2 min)

Illustrating a value of selective high assurance (~ 5 min -> …)

What is high-assurance commodity software?

Commodity software

general purpose software available for purchase by anyone on the open market;

e.g., *high volume sales & low cost*; <u>*not*</u> special-purpose software for government apps.

High assurance

mathematical methods (e.g., formal logics, number theory, information theory) used to prove *security properties* of a *computer program* or *set of programs*

e.g., beyond Common Criteria EAL7, US TCSEC A1, for the past decade

An early example

- Trusted (aka Secure) Xenix Kernel with *few* property specifications and proofs in Prolog

- *properties*: *penetration resistance* (e.g., [GG91, 92])
  - *entry* & *return point* protection
  - *parameter checking* on kernel entry
  - *time-of-check-to-time-of-use* atomicity
  - *inability to control execution of* kernel functions
  - *independence of kernel programs*
  - . . .

Why not high assurance?

[Gligor SPW 2010]

1) **High opportunity cost**

There will always be *rapid innovation* in commodity software and this will always lead to ***low-assurance*** commodity software systems

(why rapid innovation? *~0 cost of entry in software market, ~0 regulation, 0 liability*)

2) **Large commodity software systems;** aka., "*giants*" [Lampson 2004]

There will always be "***giants***" whose security properties that are *unknown* or *hard to prove*

[Lampson ACSAC 2000, CACM 2009]

3) **Defenders are rational:** *high assurance everywhere* (near perfection) is *impractical*

balance recovery cost(breach) **x probability**(breach) versus **Cost**(**prevention**);
i.e., versus **Cost**(**high assurance**)

balance tilted *away* from high assurance

Why revisit high assurance?

1. Two trends:

recovery cost(breach) **has *increased* substantially**

- cost of recovery from cybercrime ~ **1% of Global GDP**
- *average* cost/breach = **$4.24 M**; if *zero-trust* architectures, **$3.28M**; if AI/ML, **$2.9M**
- **10% Y/Y** recovery-cost *increase* (as of) 2021

formal verification cost has *decreased* dramatically

2013 - $362/SLoC - **seL4**
2014 - $128/SLoC - **Ironclad Apps**
2020 - $225/SLoC - **I/O separation kernel** (at $300K/PY)
2020 - **$40/SLoC** - **EverCrypt** libraries ~ **1/9 of 2013 cost**

=> formal verification of 50K – 70 SLoC "***wimps***" is practical

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balance is beginning to tilt *towards* high assurance

Why revisit high assurance?

2) Selective high assurance: select & *isolate* small security-critical "*wimps*" of a "giant"
& *formally prove* their *security properties*

Notation

b = no. of selected attacks to be countered by formal verification of "giant's" *source code*

C_b(verification) = ***one-time*** **cost** of verifying *at most* **b** "wimps"

C_b(recovery) = *minimum* ***recurrent annual cost*** of recovery from **b** breaches of a "giant"

C_b(recovery)·***m***·***n*** = ***market cost*** for recovery by ***m*** defenders and ***n*** > 1 years

How can a producer recoup C_b(verification)?

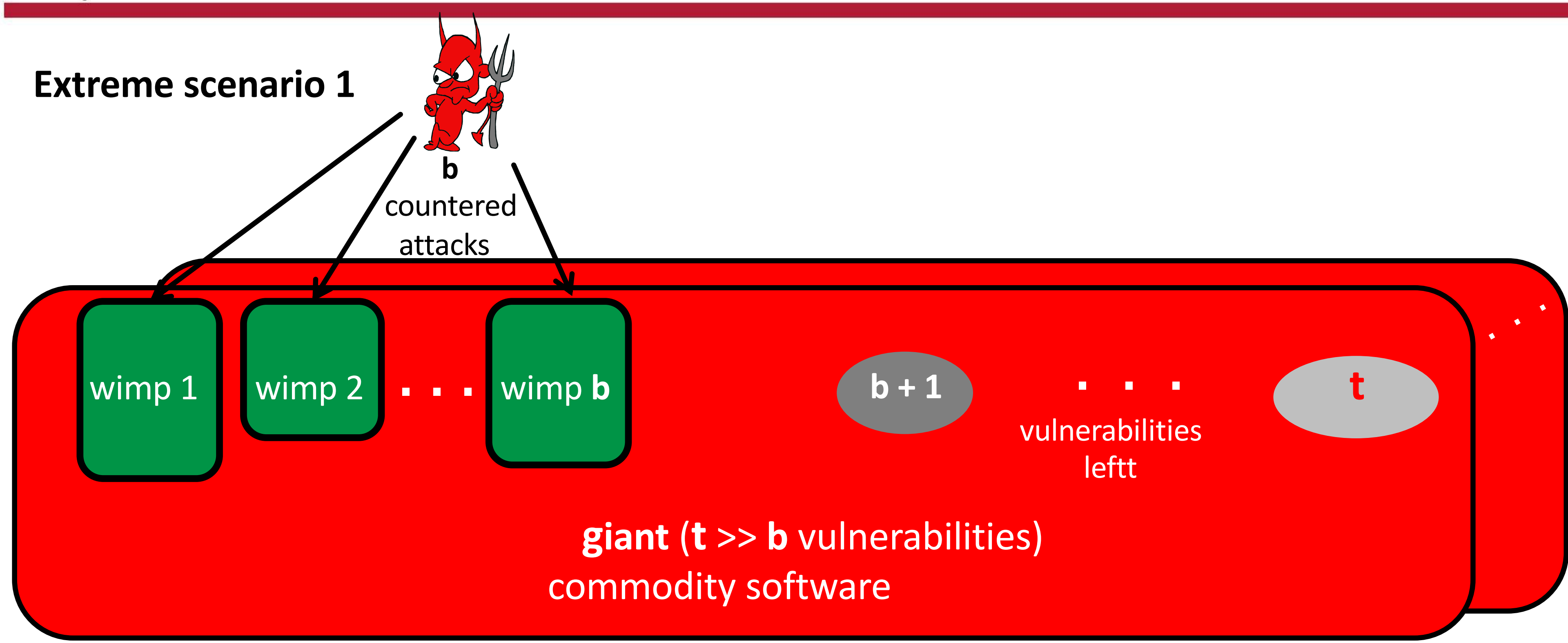
Producers & Defenders "know" the balance: C_b(verification) ≤ C_b(recovery)**x**1

Example: **b** = 3 security breaches in 42 attacks/year of US companies [VB2022]

C_3(recovery) = 3·$**2.9M** = **$8.7M**/year (already **$8.9M** in 2012)

Producer's selection:
b = 3 "wimps," size ≤ 72.5K SLoC => C_3(verification) **≤** 3·72.5K SLoC·**$40**/SLoC = **$8.7M**

Extreme scenario 1



$(m \geq 1, n)$ **-> producer** recoups cost C_b(verification) ≤ C_b(recovery)**x**1

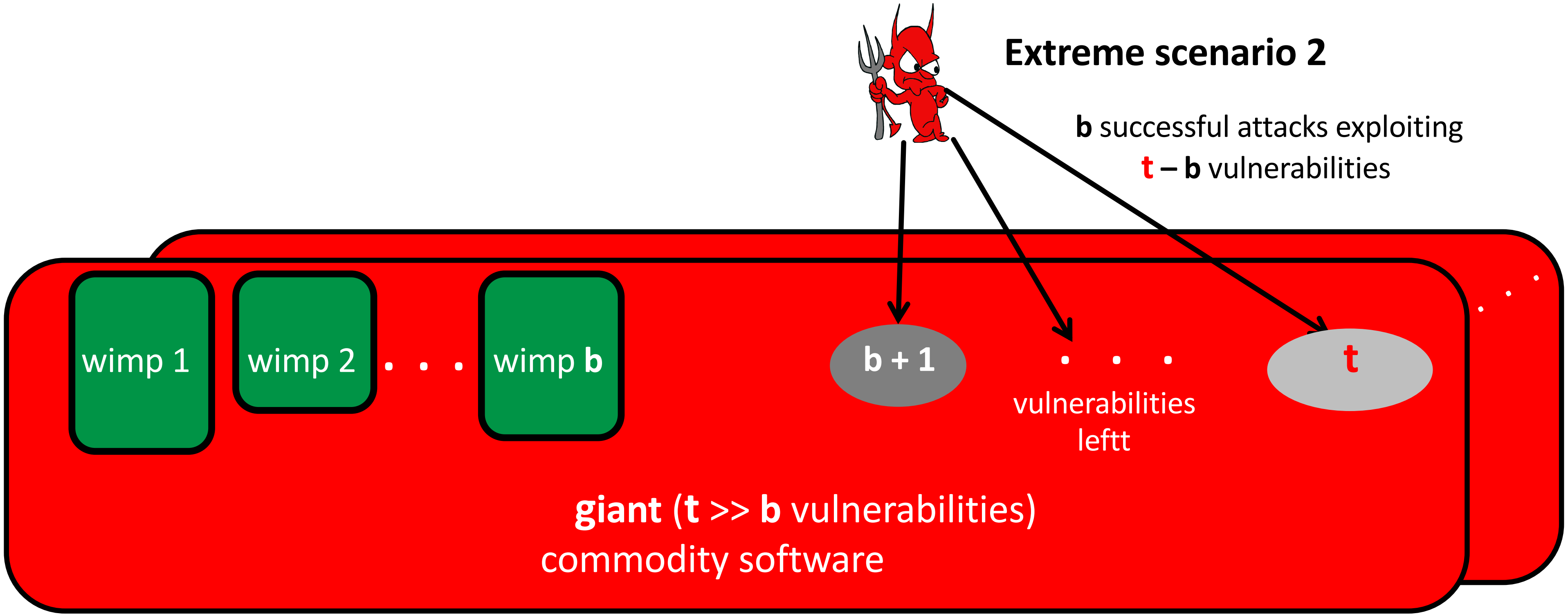
~~another choice~~: **defender$_{first}$ -> producer: 0**

defender$_{first}$'s cost: C_b(recovery) in year **1**,..., C_b(recovery) in year **n**

risk: low assurance fixes & limited deterrence

producer ~~**controlled**~~ ***m*** >> 1 **=> producer** increases price by C_b(verification)/***m*** = ***negl***.(***m***)]

Extreme scenario 2



($m \geq 1, n$) **->** **producer** recoups cost C_b(verification) **≤** C_b(recovery)**x**1

find *smallest* ϵ: $(1-\epsilon)\cdot C_b(\text{recovery})\cdot \boldsymbol{m}\cdot\boldsymbol{n} + C_b(\text{verification}) \leq C_b(\text{recovery})\cdot\boldsymbol{m}\cdot\boldsymbol{n}$

=> smallest $\epsilon > \mathbf{1}/(\boldsymbol{m}\cdot\boldsymbol{n})$. Then, setting $\epsilon = \mathbf{b}/(\mathbf{t}\text{-}\mathbf{b})$ => $\boxed{\mathbf{t} < \mathbf{b}(\boldsymbol{m}\cdot\boldsymbol{n} + \mathbf{1})}$

producer guesses $\boldsymbol{m} > \mathbf{m_0}$ and increases price by C_b(verification)/$\boldsymbol{m}$

producer recoups C_b(verification) in *all attacks* between **Extreme scenarios 1** & **2**

Estimation of (**t**, $\mathbf{m_0}$, $\mathbf{n_0}$): producer needs *a <u>very small</u>* market ($\mathbf{m_0}$, $\mathbf{n_0}$): *recoup cost*

Problem: surveys *cannot* reveal **t**, max no. of vulnerabilities/"giant"
s, no. of "giants"/defender
r, no. of responders/defender (typically **r** = 1)
m, no. of different defenders using same "giant" & ***n*** > 1

Example 1: **V** = total no. of *un-remediated vulnerabilities* of *all* defenders, *all* **R** responders

$V = t \cdot s \cdot R/r \Rightarrow t = r \cdot V / s \cdot R \;\&\; r/s \leq 1 \Rightarrow \boxed{t \leq \lceil V/R \rceil}$

e.g., **b** = 3, **R** = 47%×634, **V** = (1 – 46%) ×1.1M

=> **t** = 1994, $\mathbf{n_0} = 2$, $\mathbf{m_0} = 332$ / $\mathbf{n_0} = 7$, $\mathbf{m_0} = 95$ < 5.3% all companies on US stock exchanges

Example 2. **v** = lower bound on no. of *un-remediated vulnerabilities/defender*
s = average no. of applications/defender (another survey)

b = 3, $t \geq v/s$, **s** = 200, **v** ≥ 50,000

=> **t** ≥ 250, $\mathbf{n_0} = 2$, $\mathbf{m_0} = 42$ / $\mathbf{n_0} = 7$, $\mathbf{m_0} = 12$

The need for selective high assurance

Start with

expected **Cost**(defender) **=** **recovery cost**(breach) **x** **probability**(breach)

Show that *minimization of*

- **probability**(breach) &
- **recovery cost**(breach)

=> ***selective high assurance***

Minimize probability

- separate ***D****eterrence* from ***A****ssurance* [Lampson2009, GW2011]

  => separate probability(breach) into two ***non-independent*** components

  - ***A****ssurance* **->** **probability_A**(breach)

  - ***Deterrence*** **->** **probability_D**(breach)

- minimize

  - **probability** = ***min***(**probability_A, probability_D**) ≤ upper limit

Separation

probability$_A$(breach)

1 → 0

breach-prevention
assurance

low → **high**

- *security functions*
  verification, monitoring,
  recommendations, etc.

- *operational assurance*
  principles;
  e.g., least privilege,
  separation of duty,…

- *correctness assurance*
  models, design,
  implementation;
  proofs,
  security testing, etc.

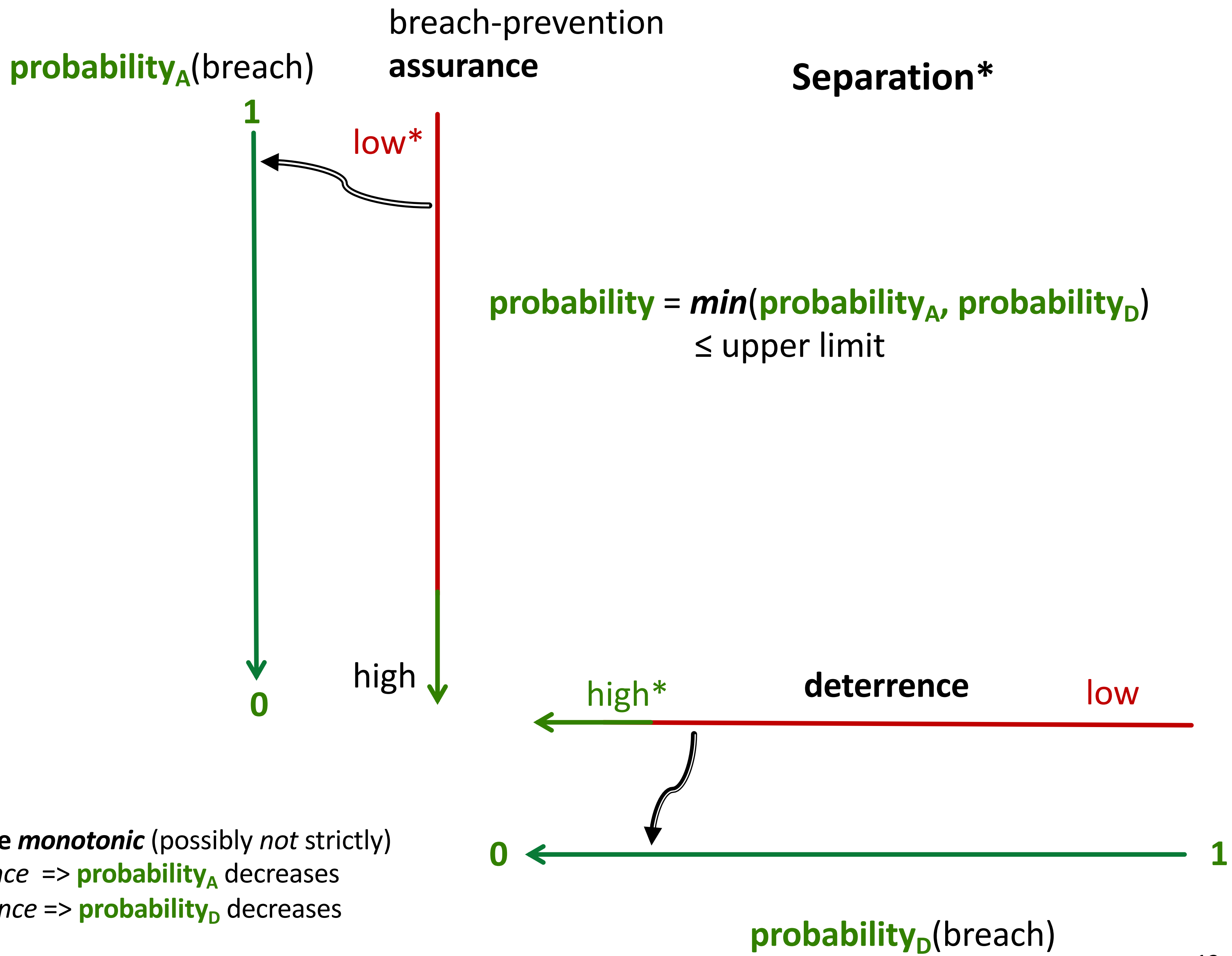
high ← **deterrence** ← **low**

- increased attack cost, detection & response
  audit & punishment, name & shame, etc . . .

0 ← 1

probability$_D$(breach)

Separation*



mappings "~>" are *monotonic* (possibly *not* strictly)
- increase ***Assurance*** => **probability$_A$** decreases
- increase ***Deterrence*** => **probability$_D$** decreases

"In fact, real-world security depends mainly on deterrence, and hence on the possibility of punishment." [Lampson, CACM 2009]

Defenders are rational [Lampson ACSAC 2000, CACM 2009]

- low assurance: **$probability_A$(breach) -> 1**

- **high** deterrence: **$probability_D$(breach) -> 0**

$$probability_D = \mathit{min}(probability_A, probability_D)$$

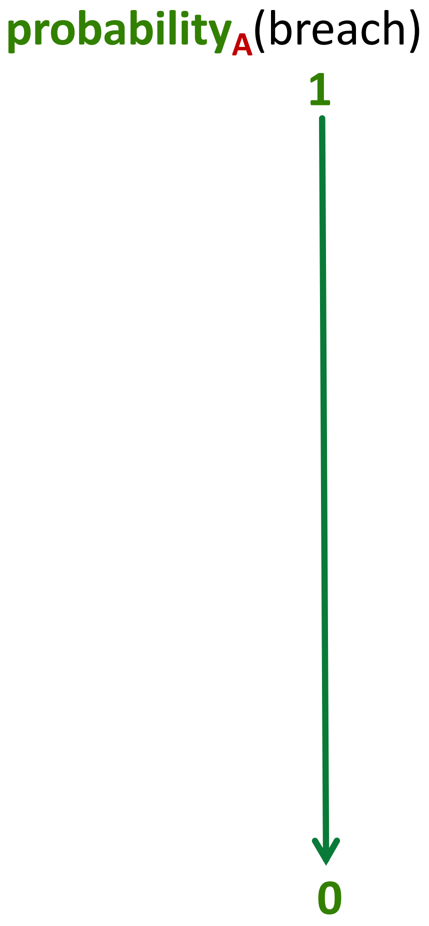
However, defenders must "assume breach" [NSA 2001, VB2022]

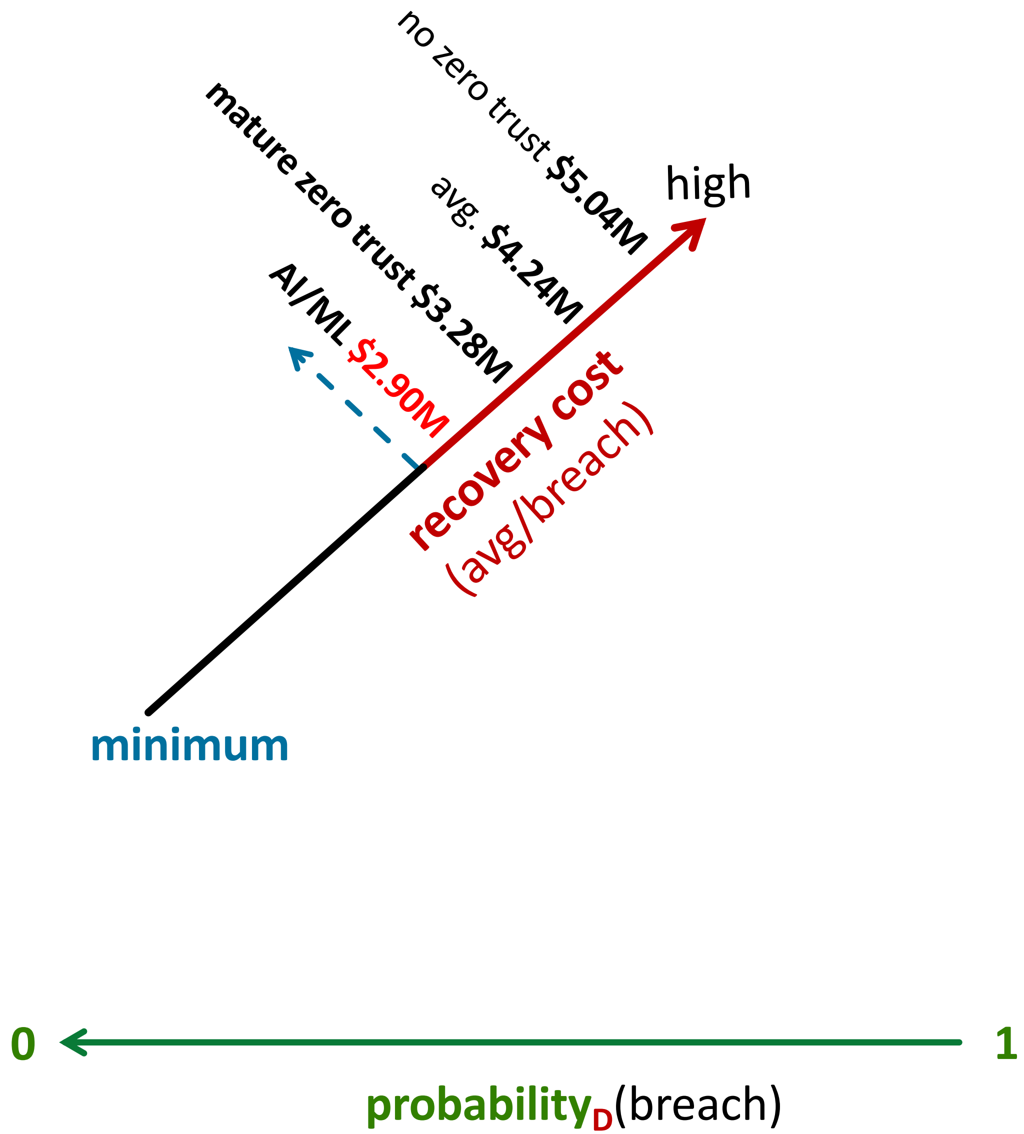
e.g., there is *no deterrence* of *state-sponsored attackers*

=> **$probability_D$(breach) -> 1**

=> **Cost**(defender) = **recovery cost**(breach) x **1**

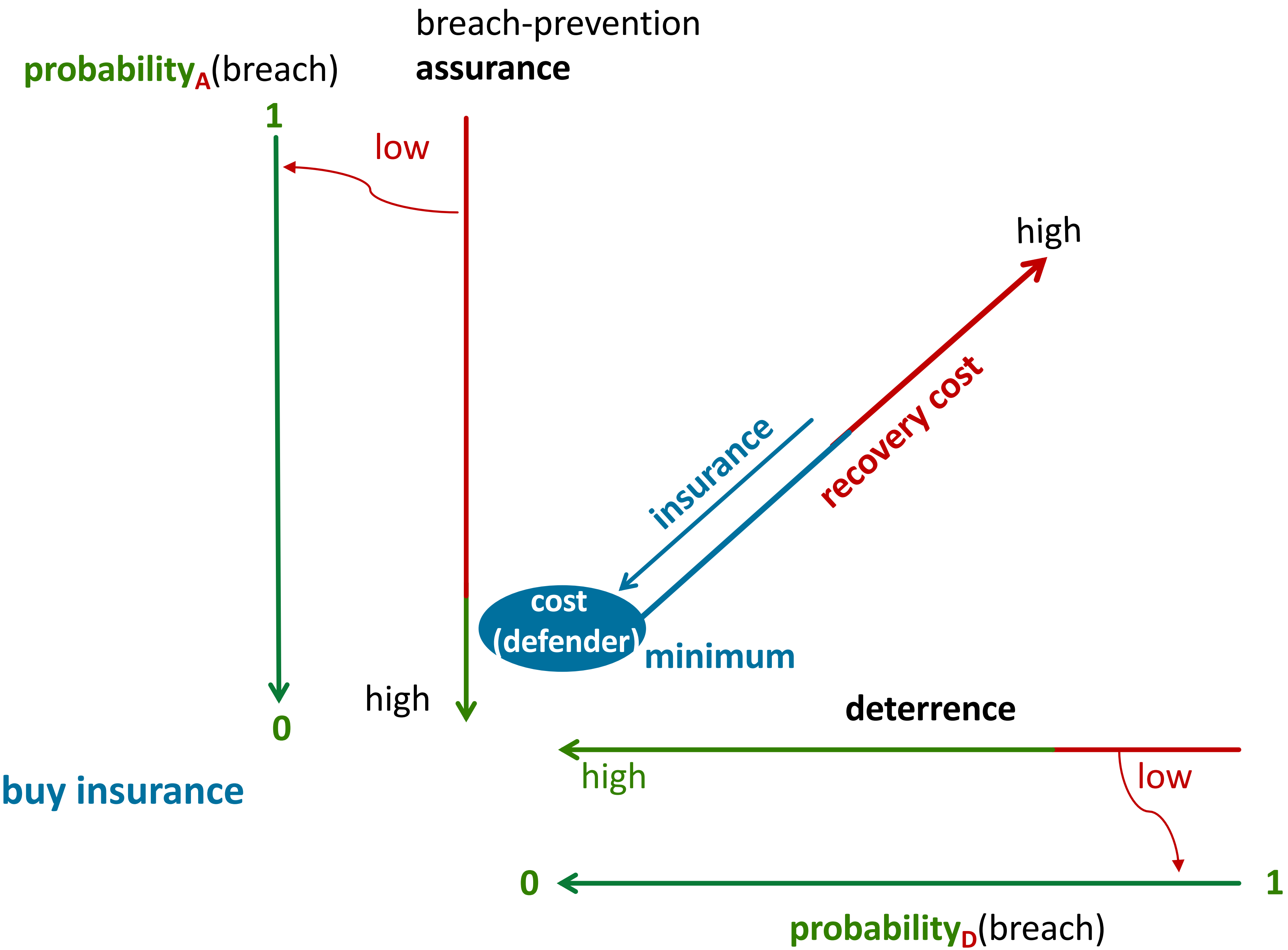
Minimize **recovery cost**



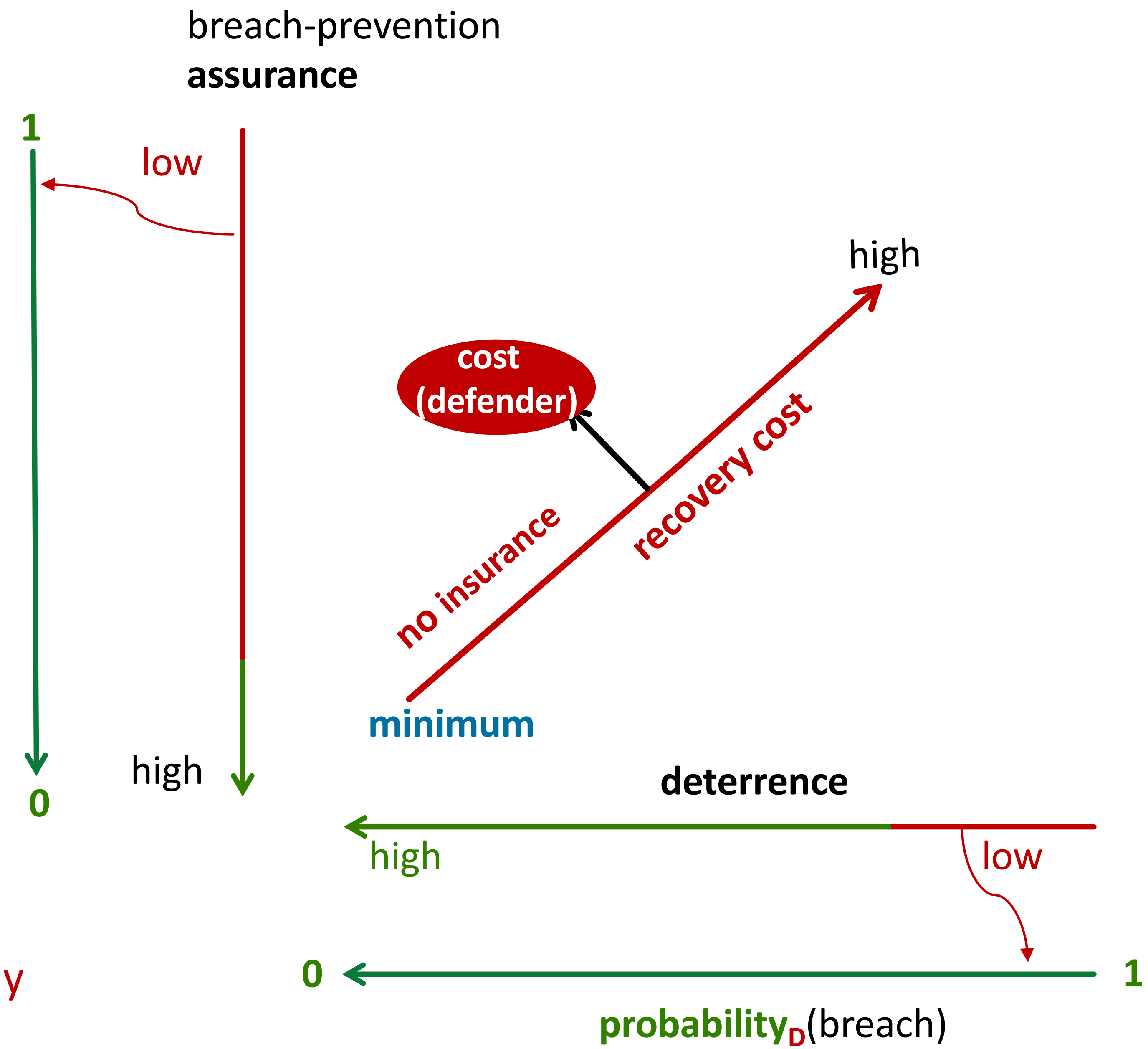


Example: IBM Cost of Data Breaches (2022)

Problem: recovery cost ≠ minimum



Solution: **buy insurance**



Problem:
many (> 50%) defenders
can afford but cannot buy
insurance

No alternative is left?

“assume breach” mindset [NSA2021, VB2022]

- **Assurance** – **low**: **probability$_A$**(breach) **-> 1**
- **Deterrence** – **low**: **probability$_D$**(breach) **-> 1**

- **Recovery cost** – **high**: **no insurance**

What is left is . . .

- **Selective High Assurance** => **probability$_A$**(breach) ≤ **upper limit**

- **Deterrence** - low: **probability$_D$**(breach) -> **1**

- **recovery cost** - high: no insurance

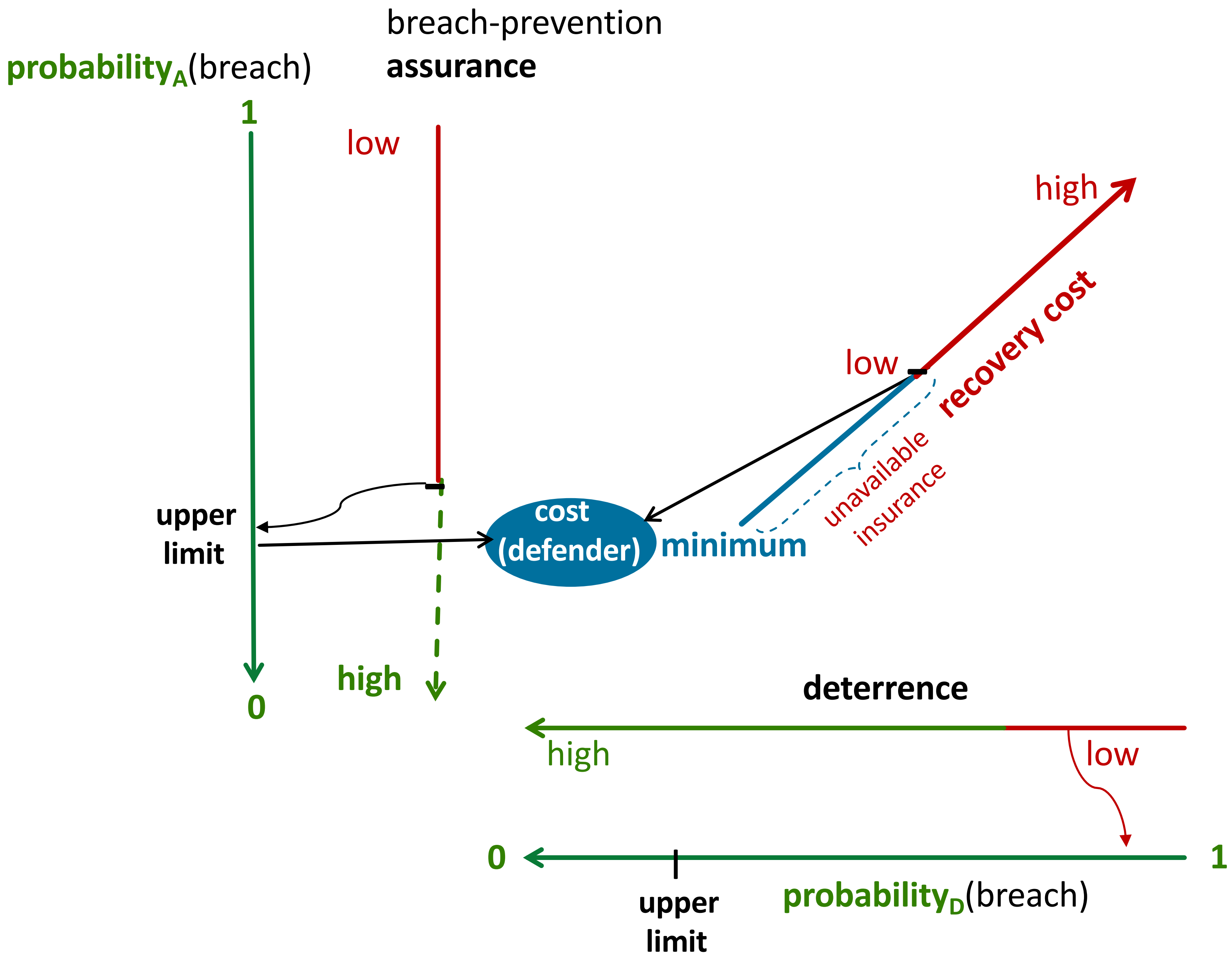
Goal

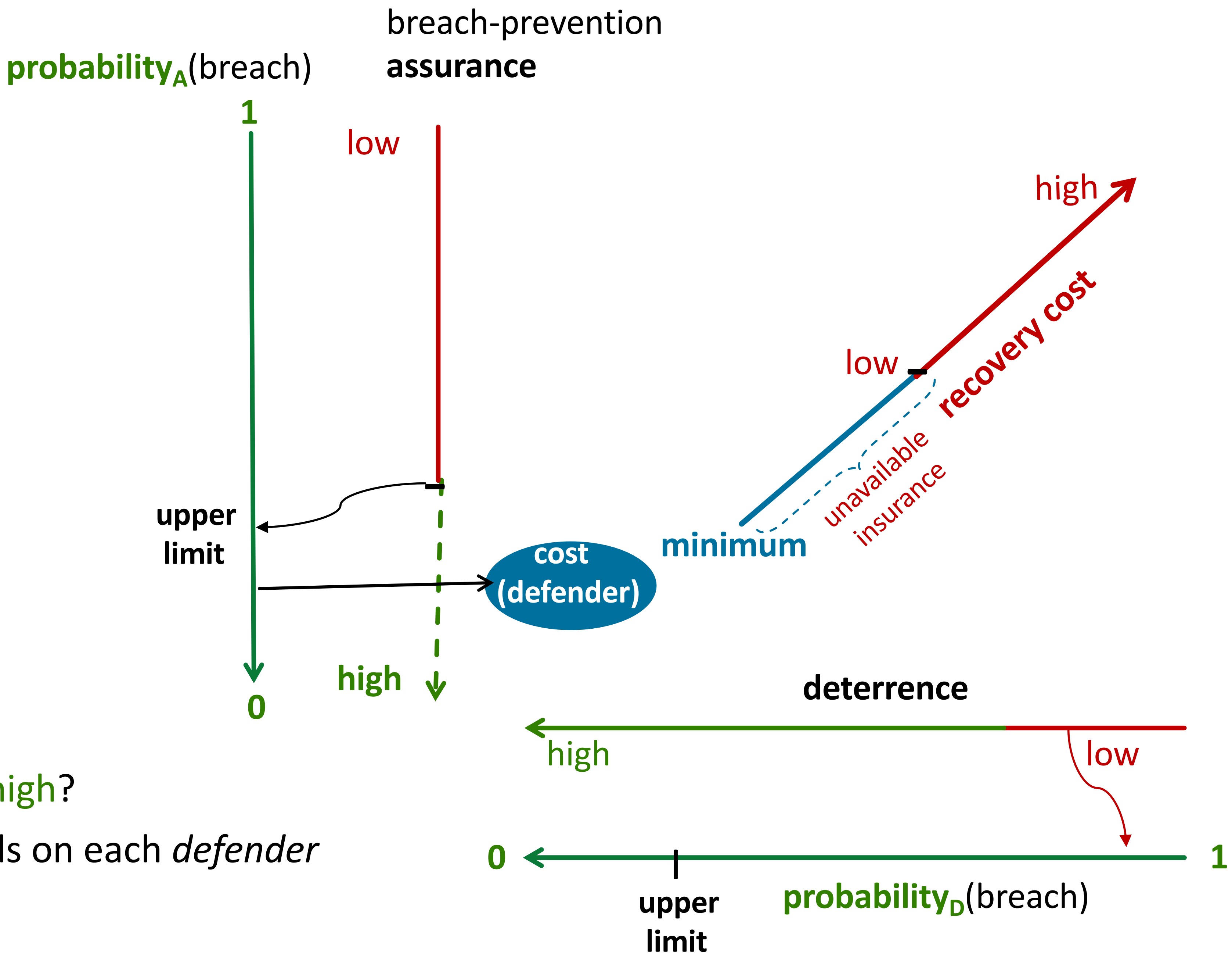
expected **Cost**(defender) = **probability$_A$**(breach) **x** **recovery cost**(breach)

≍ **insurance cost**(breach)

probability$_A$(breach) ≍ **insurance cost**(breach)/ **recovery cost**(breach)

≤ **upper limit**


breach-prevention
assurance
probability$_A$(breach)
1
low
high
recovery cost
low
upper
limit
cost
(defender)
minimum
unavailable
insurance
0
high
deterrence
high
low
0
1
upper
limit
probability$_D$(breach)



Question:

how high is high?

. . . it depends on each *defender*

A Challenge

Find a *<u>defender-independent</u> value* of high assurance for commodity software systems

e.g., find a *lower-bound value* that *depends only on the commodity software itself*

Goal: for *a <u>selected</u> set of breaches* of a *commodity software system*
selective high assurance **=>** ***probability***$_A$(breach) ≤ **upper limit**

Addressing the Challenge: Hypothesis of Formal Methods

Formal methods **=>** no vulnerability **=>** no security breach **=>** ***probability***(breach) = **0**

A Hypothesis Interpretation: Selective High Assurance

In general, for a *set of attacks* against a *selected source code*,
formal methods **=>** *attacks* are countered in *source code*
=> ***probability***(breach in <u>selected *source code*</u>) ≤ **upper limit (-> 0)**

How to do it?

For a *set of CVEs/CWEs* referring to the unverified *source code*,
formal methods **=>** *CVE/CWEs exploits <u>do not exist</u>* in verified source code
=> ***probability***(CVE/CWE exploit exists in *<u>source code</u>*) **= 0**

Illustrating a Value of Selective High Assurance (SHA) – Steps

1. Select a software system – i.e., SCION as the first example -- with:
   - *formally code-level verified security properties*,
   - substantial size and complexity,
   - internet-facing interfaces,
   - known attack surfaces

2. Select from over 200K vulnerabilities of CVE/CWE databases (MITRE, NIST) those
   - *that are countered by the formally verified protocols and services* of SCION
   - others that are related to selected ones; e.g., similarities and dependencies

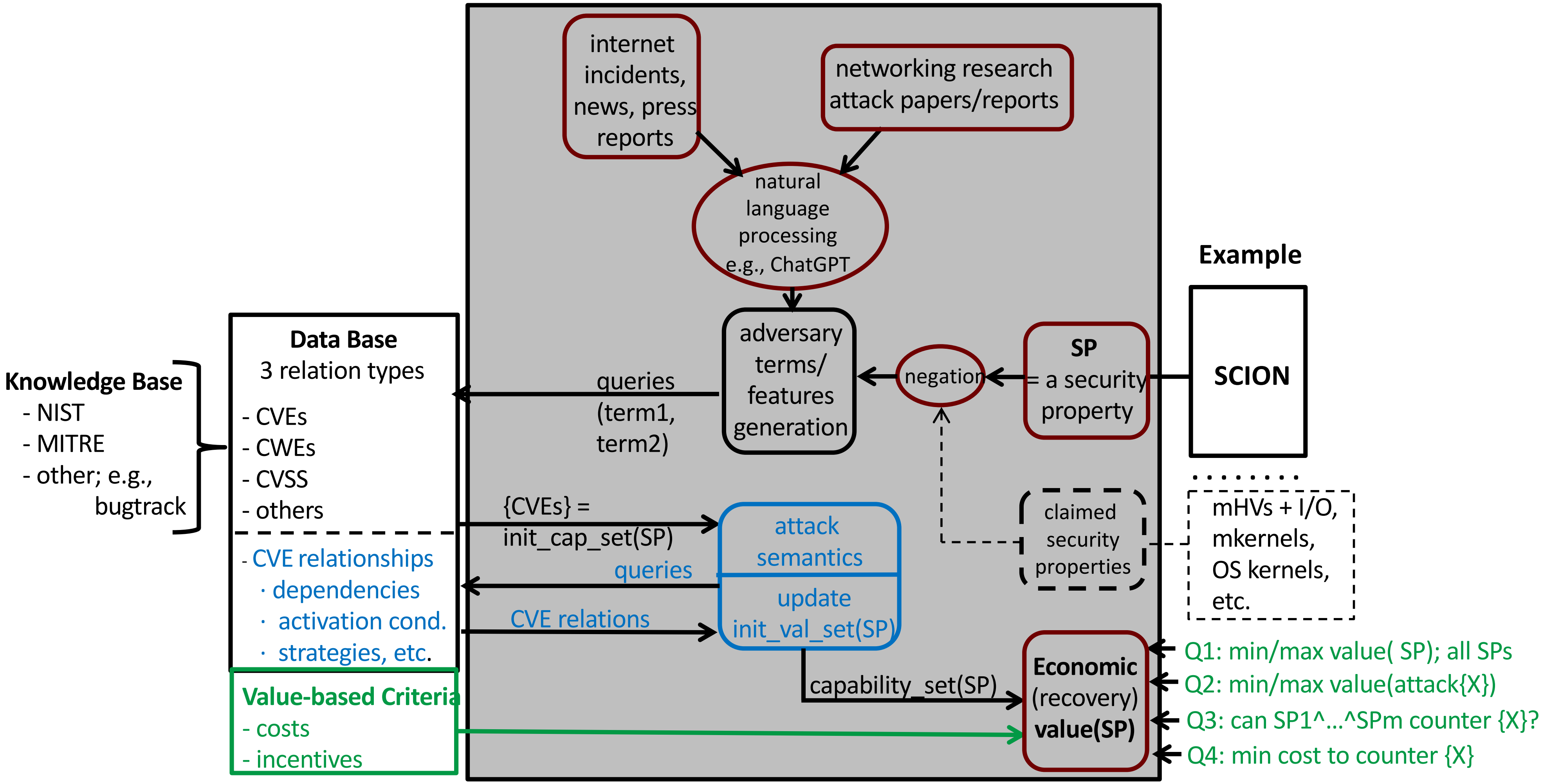
Define as many exploits (e.g., published and unknown attacks) as possible for the CVEs found in Step 2. Illustrate different attacker and defender values

Determine an industry-sanctioned *average cost of recovering from breaches caused by these exploits* in the *ordinary Internet*

The value obtained represents an *average lower bound of the formal methods* that enables SCION to counter those breaches.

Illustrating a Value of Selective High Assurance – Project Overview

NUS (Zhenkai Liang) - **ETH** (A. Perrig and D. Basin) – **CMU** (V. Gligor)



Q & A