# Forecasting software vulnerabilities

## Probability Density Functions and Time Dependency Trees

C.E. Budde R. Paramitha F. Massacci

14th March 2024

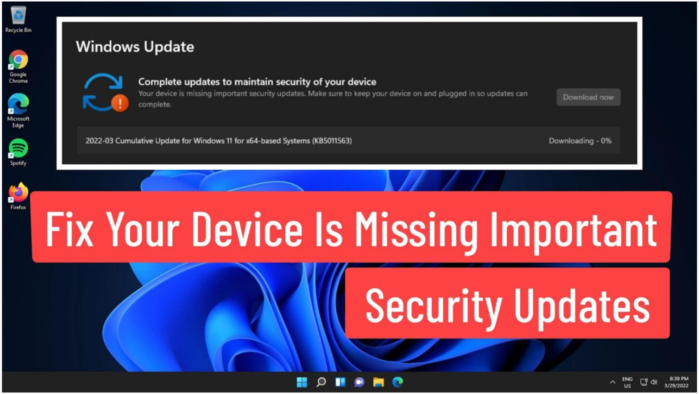
ProSVED final event symposium

# Talk overview

1. Introduction
2. Background
3. Forecast model
4. Conclusions

# Introduction

# Those annoying security updates



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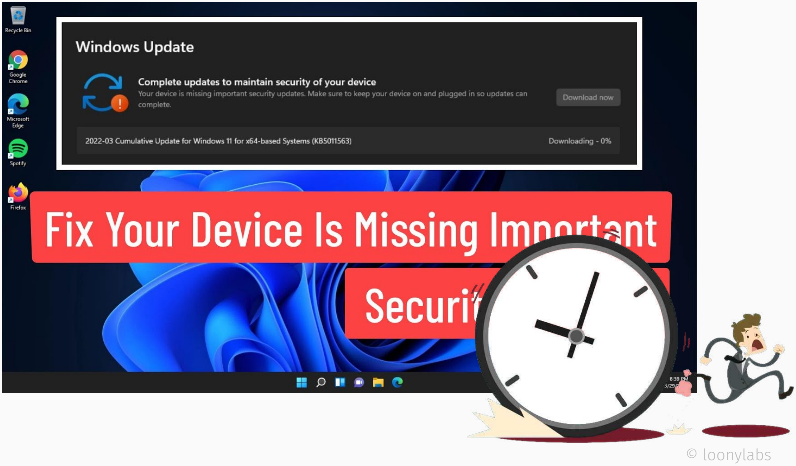

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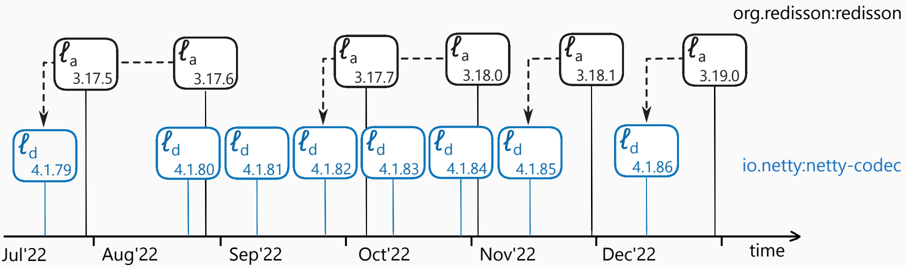

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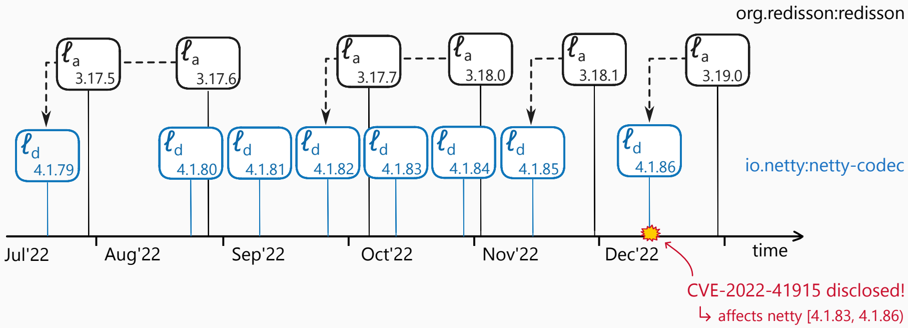

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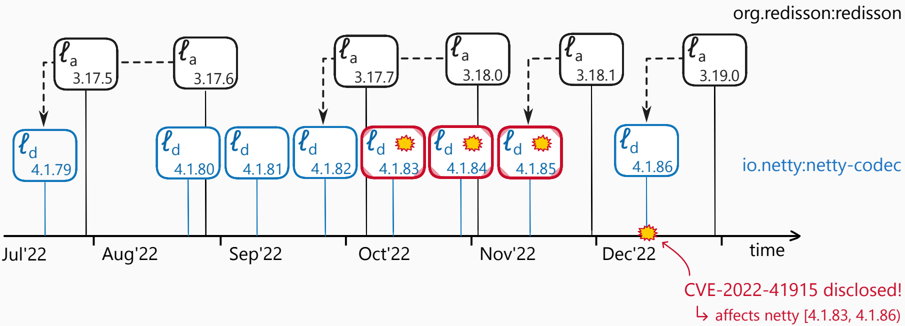

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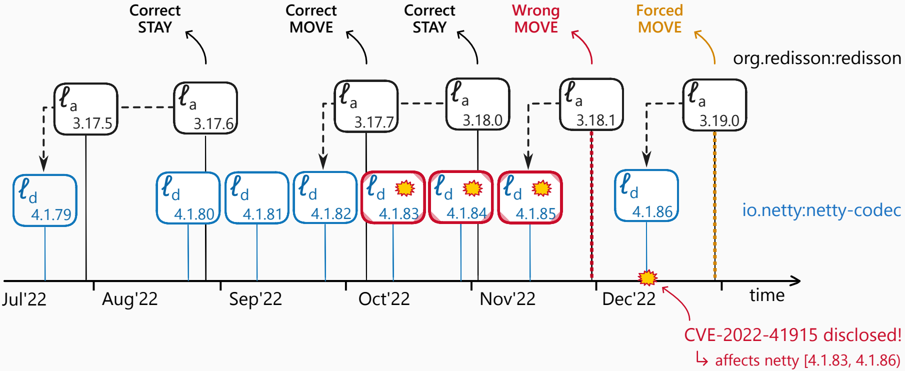

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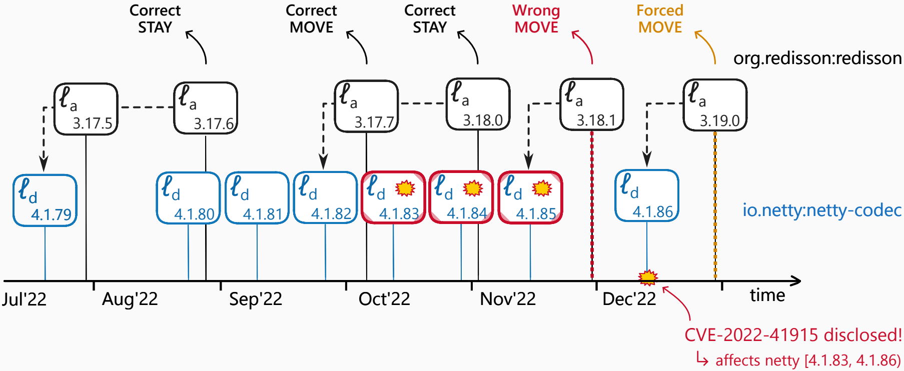
## Hindsight!

© j4p4n



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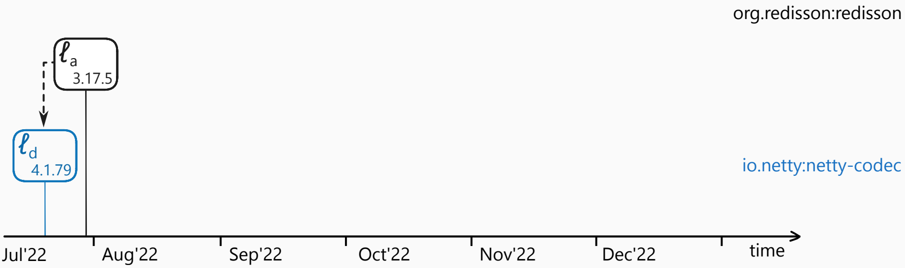

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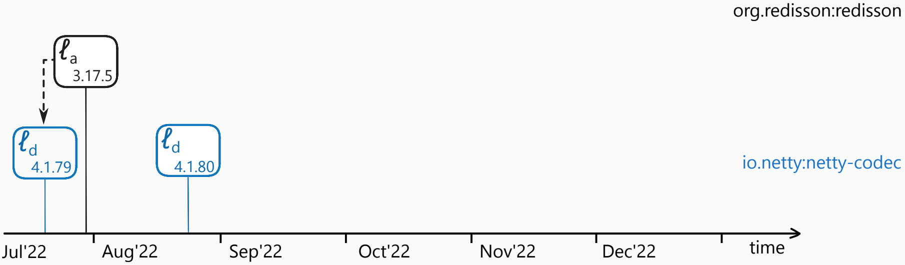

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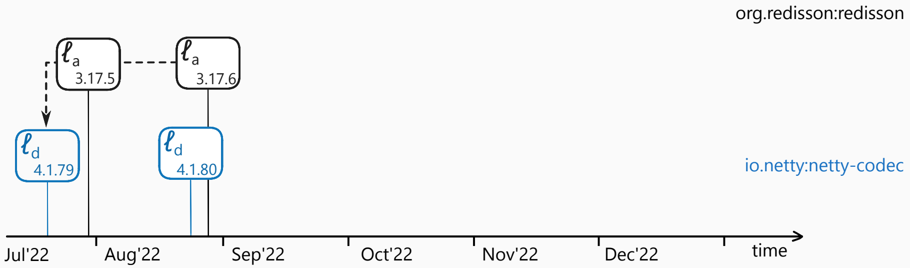

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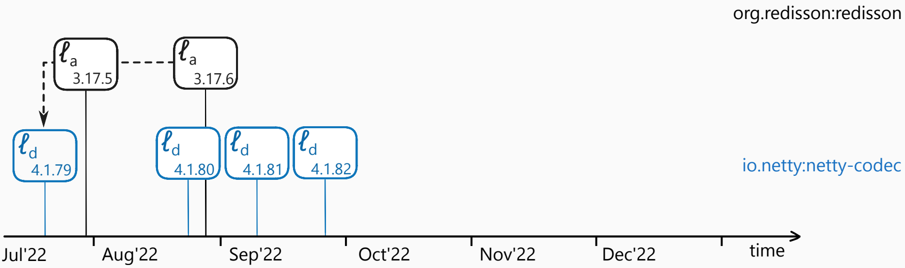

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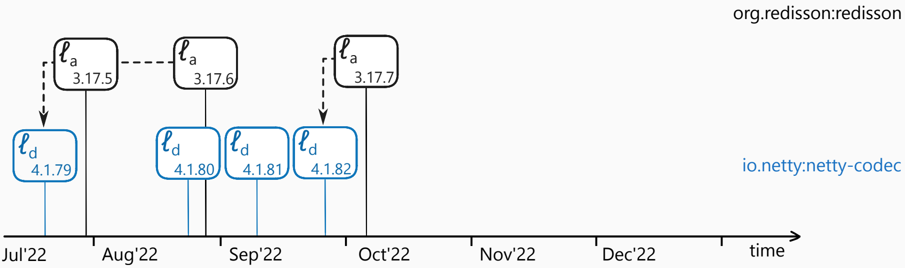

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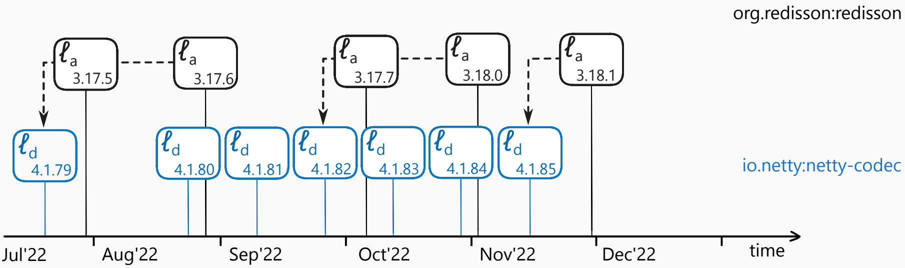

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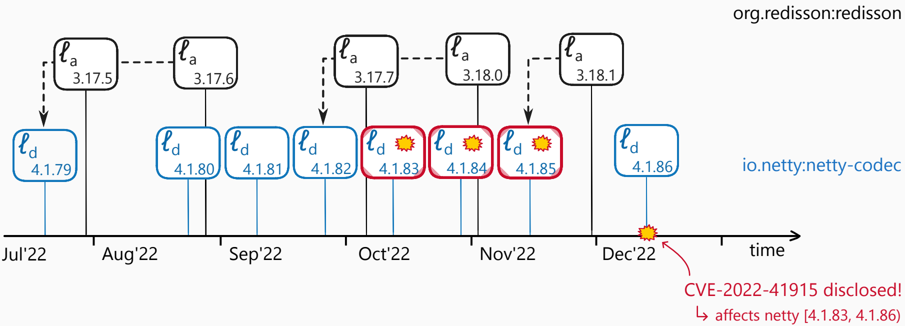

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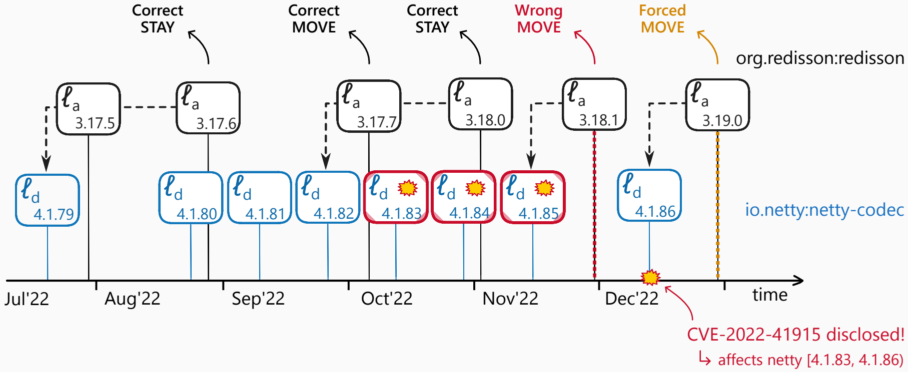

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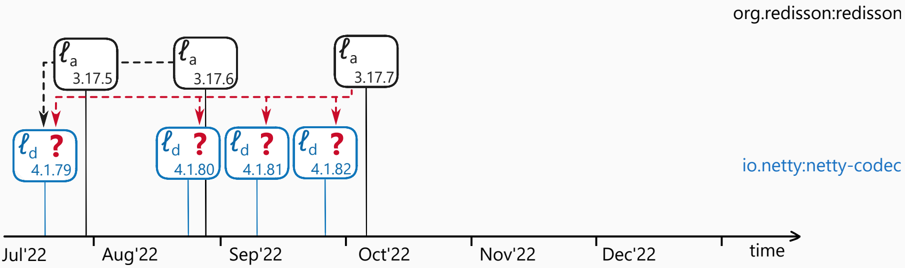

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**Q2** Which other factors affect $\Pr(\text{vuln.})$?

- ▷ measurable software metrics

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    - … but check the work of the EPSS!

# Background



| Work | Goal | | Data | | | | Method | | | Approach | | | Projects/Libs. | | Purport |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Disc. | Pred. | CVEs | Code | VCS | Dep. | Corr. | Clas. | T.Ser. | AH | SA | ML | Language | # | |
| [WTT+24] | ✓ | | | ✓ | | | ✓ | ✓ | | | | ✓ | C/C++ | 20 | Find vulnerabilities regardless of existent logs such as CVEs (although CWEs may be used). This includes formal methods and static/dynamic code analysis. |
| [BES+20] | ✓ | | | ✓ | | | | ✓ | | | | ✓ | C | 3 | |
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| [MW10] | ✓ | | ✓ | | ✓ | | ✓ | | | ✓ | ✓ | | C, ASM | 3 | |
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| [GOP21] | ✓ | | ✓ | ✓ | | | | ✓ | | | | ✓ | Java | 7 | |
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| [KWLO17] | ✓ | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | | C/C++ | 8 | |
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| [PSS+21] | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | Java, Ruby, Python | 450 | |
| [LRW22] | | ✓ | ✓ | | | | | | ✓ | | ✓ | ✓ | Agnostic | 4 | Time regression to predict vulnerabilities from NVD logs, but the models do not use domain-specific data relevant for security. |
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| [LST+21] | ✓ | | ✓ | ✓ | | ✓ | | ✓ | | | | ✓ | Java | >300k | |
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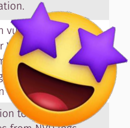

**Q2** Pr(vuln.) as function of software metrics

**Q1** Pr(vuln.) as function of time

**Q2** $\Pr(\text{vuln.})$ as function of software metrics

- ML & statistical analysis to correlate SE metrics to existent vulnerabilities

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**Q1** $\Pr(\text{vuln.})$ as function of time

- time-regression models on CVE publications ($\approx$ FinTech)

# Gap analysis

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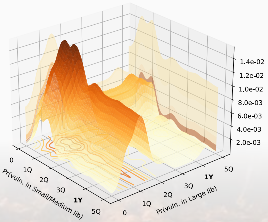
**We propose white-box model(s) to fill these gaps**

# Forecast model

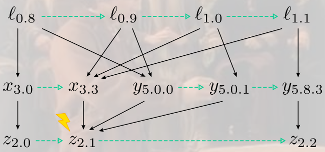


# Forecast model

CVE root-lib PDFs

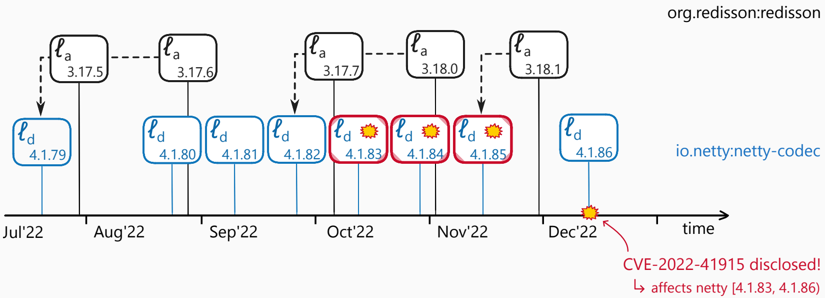





Time Dependency Trees

# Publication of CVE since time of code release



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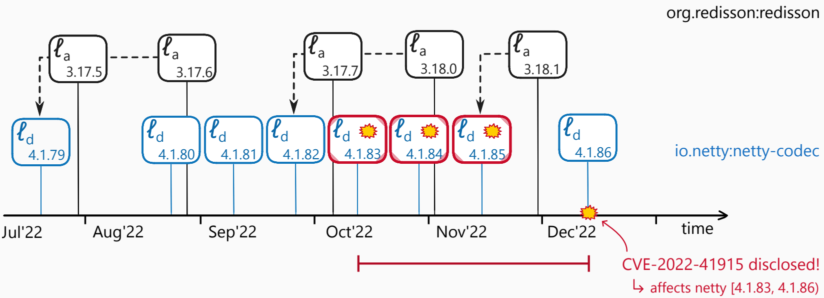

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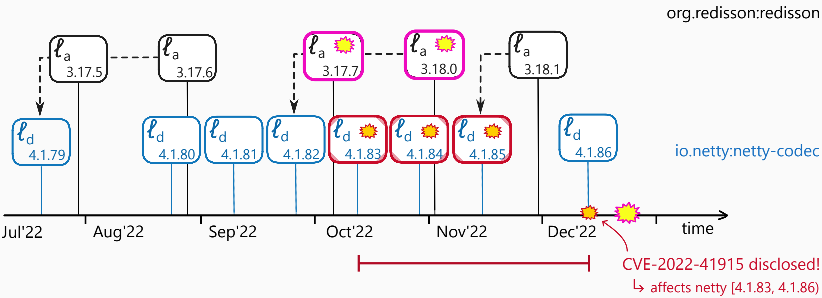

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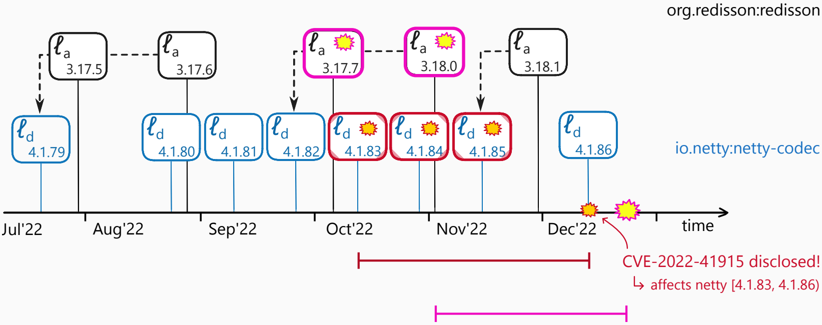

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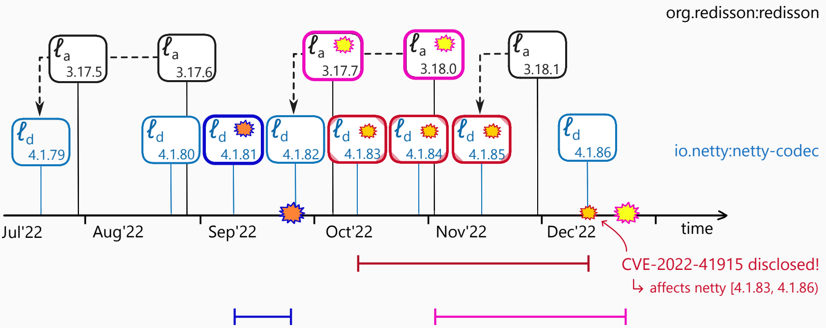

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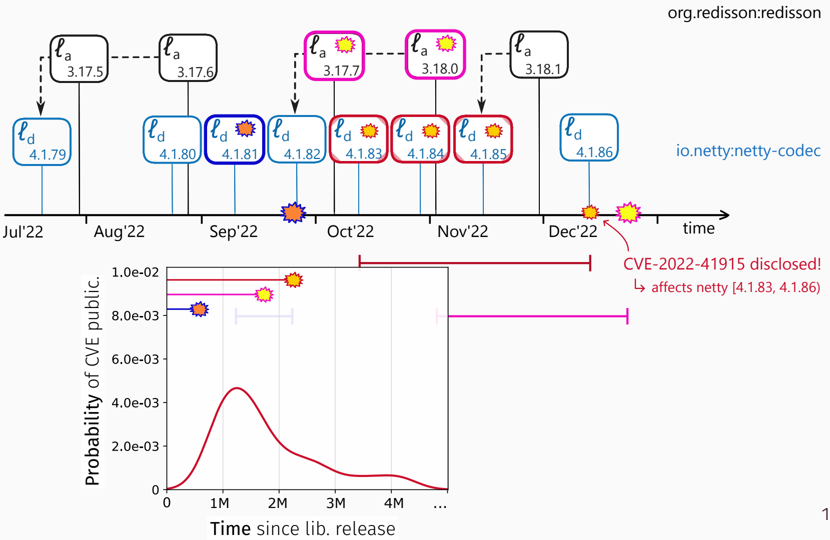

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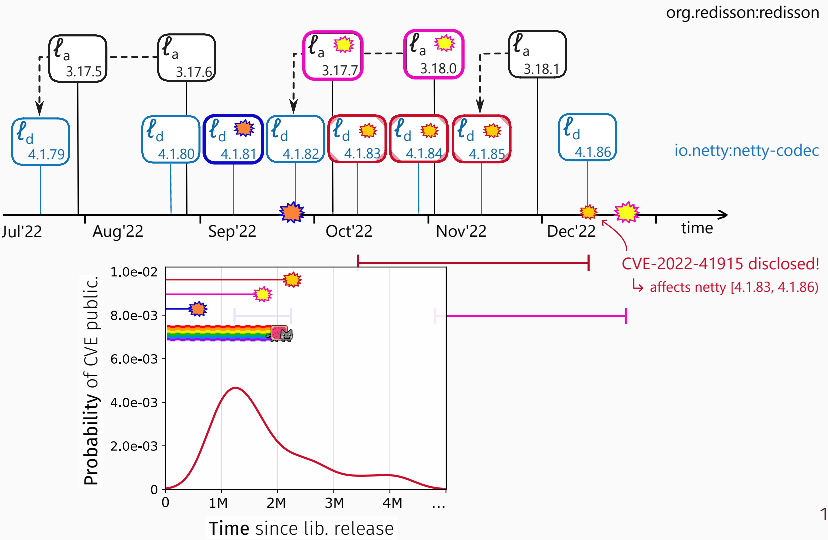

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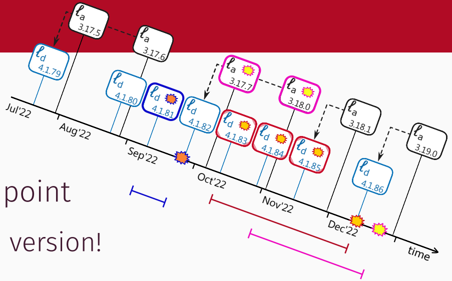


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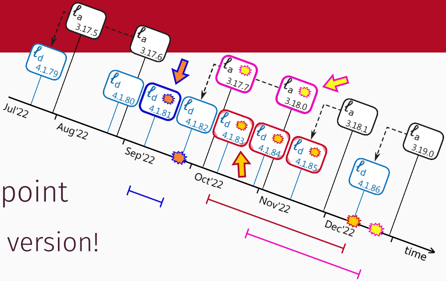


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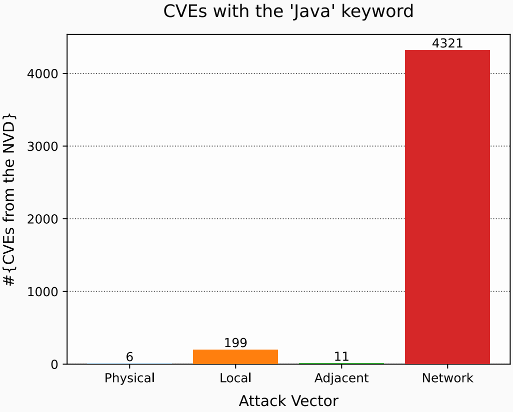
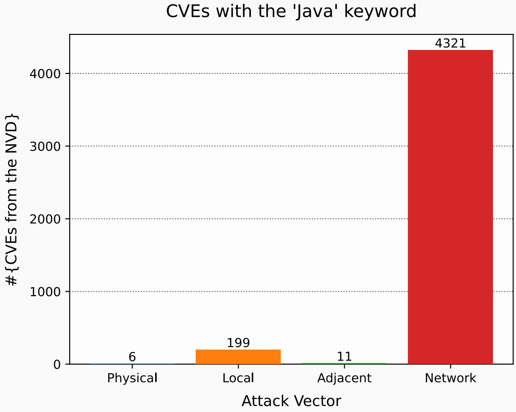


## Used in remote networks



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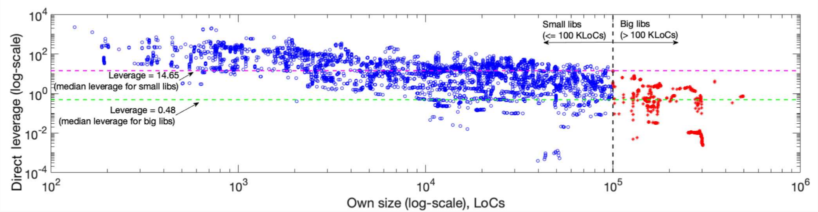
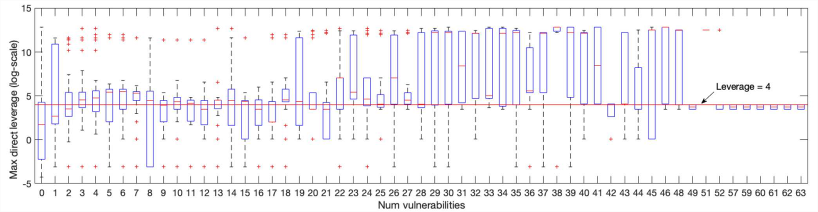
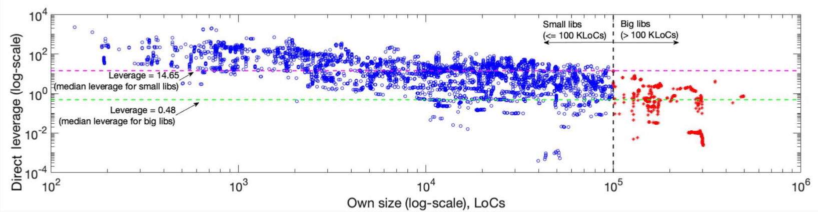
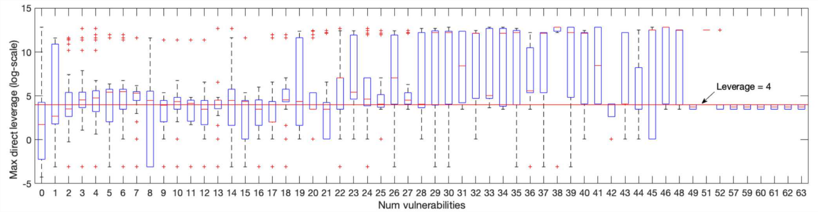


# Security-relevant code metrics

## (Own) Code size



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Own-code size

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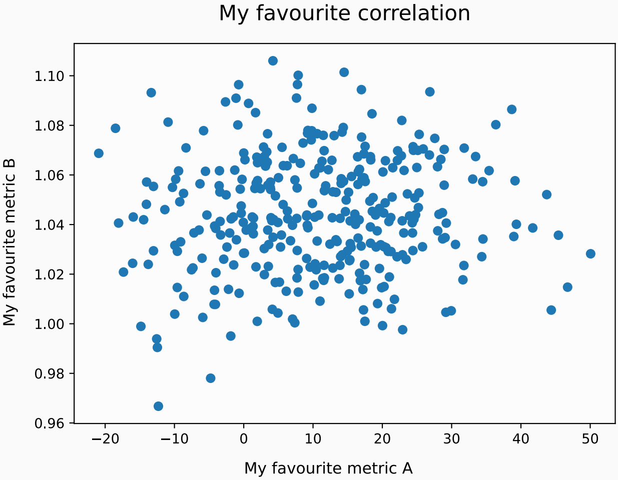


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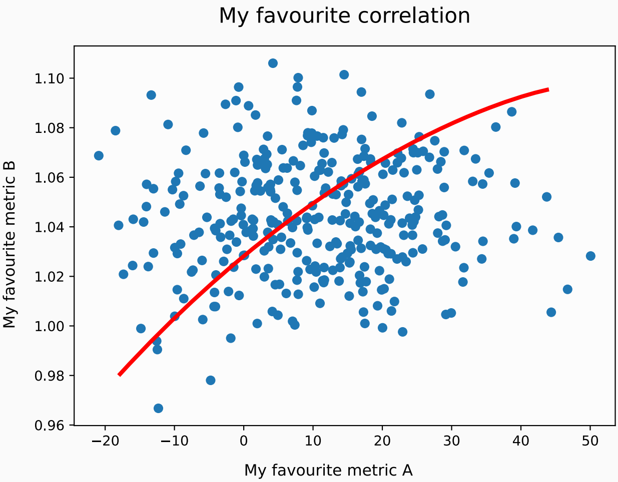


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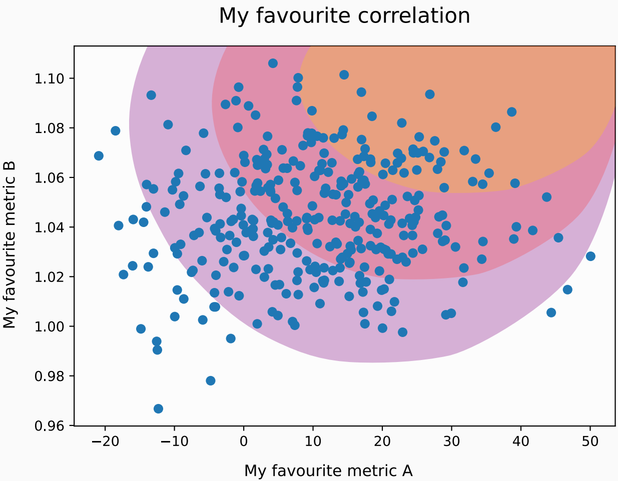


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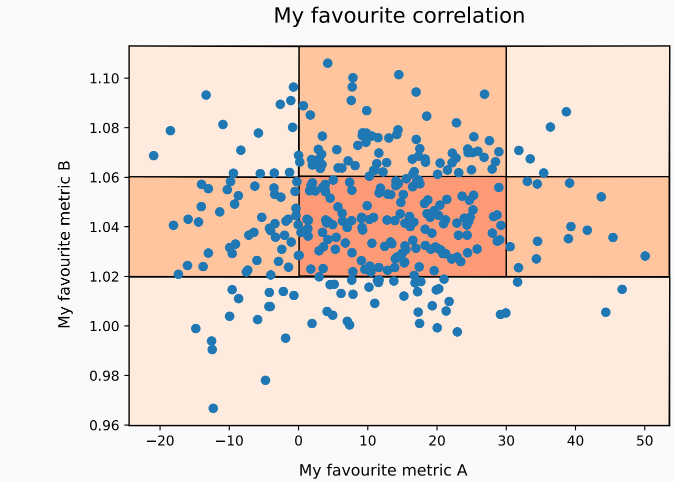


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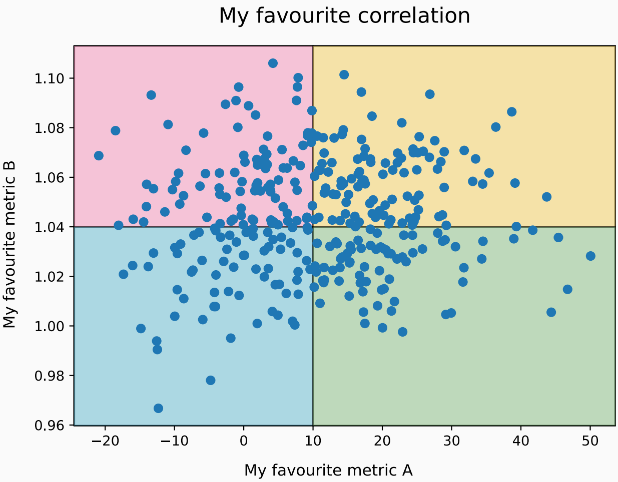


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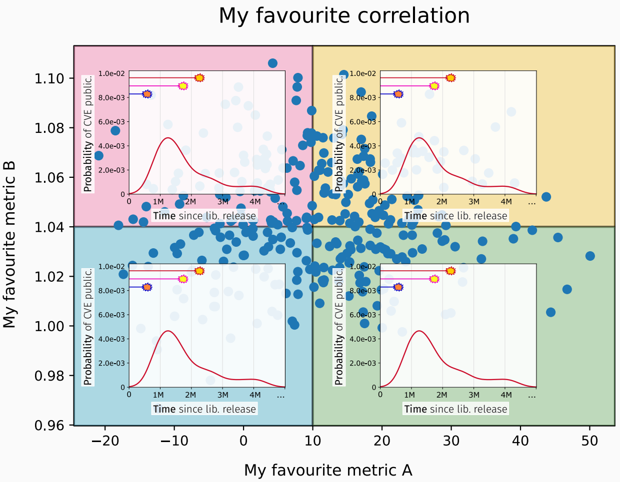


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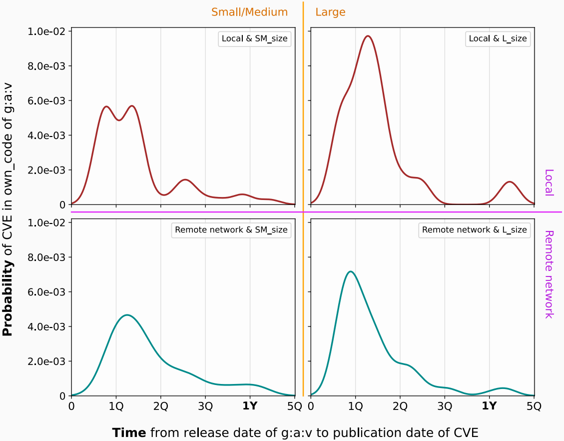


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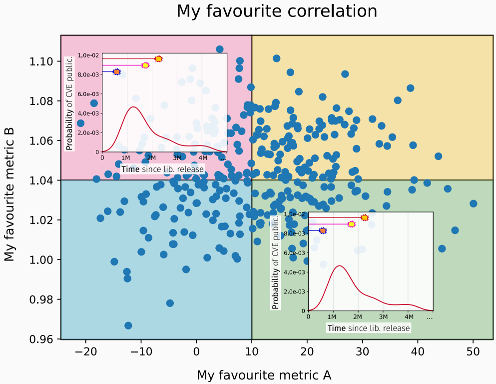

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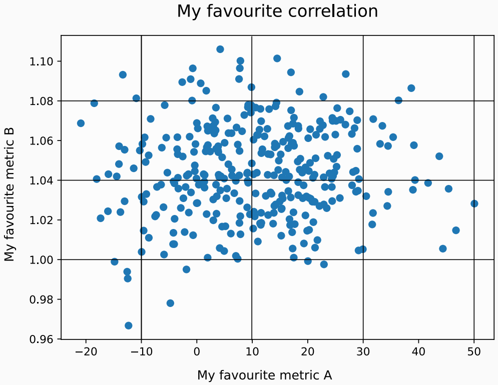

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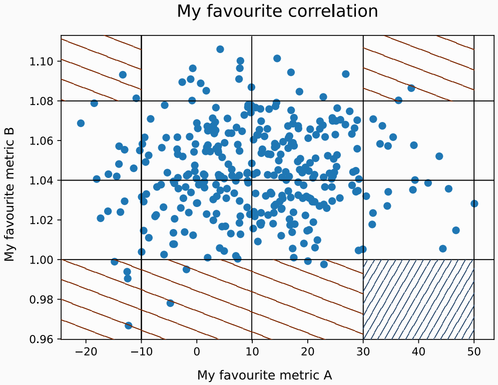

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- Clusterisation mustn't be too thin
  - few divisions per metric-dimension
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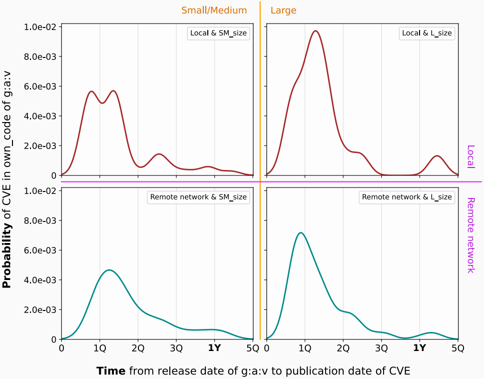
**Enough!**

Gimme results

# Here ya go



Small/Medium
Large
Local & SM_size
Local & L_size
Remote network & SM_size
Remote network & L_size
Local
Remote network
Probability of CVE in own_code of g:a:v
Time from release date of g:a:v to publication date of CVE
1.0e-02
8.0e-03
6.0e-03
4.0e-03
2.0e-03
0
0
1Q
2Q
3Q
1Y
5Q

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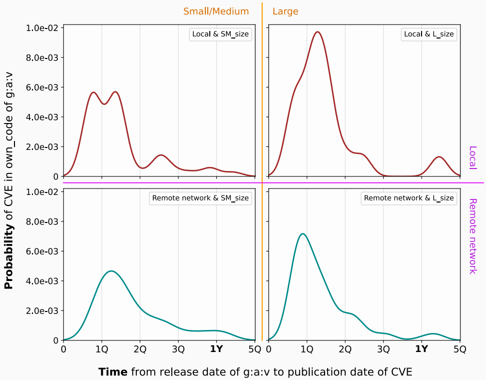


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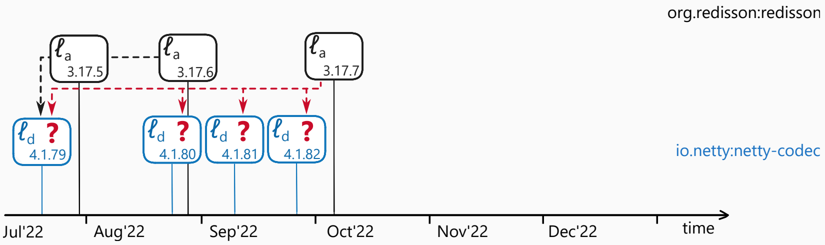

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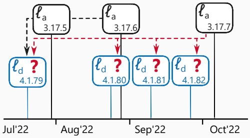

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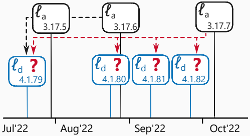


**Q:** $\mathrm{Pr}_{A,B}(t) =$ probability of vuln. of $A \xrightarrow{t} B$ as a function of $t$

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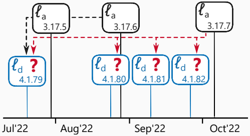


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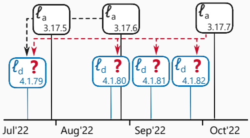


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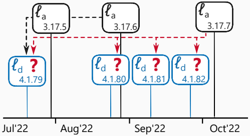


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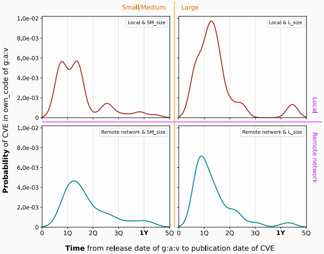

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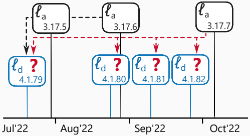


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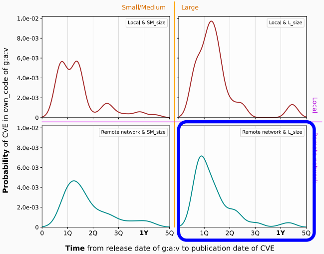


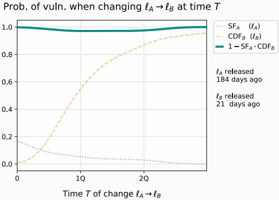


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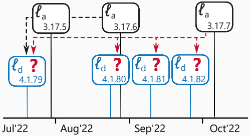


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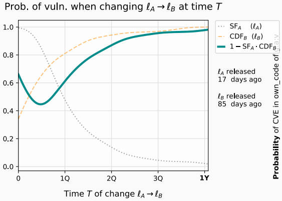


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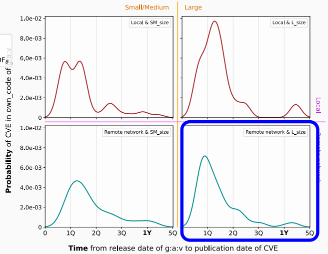


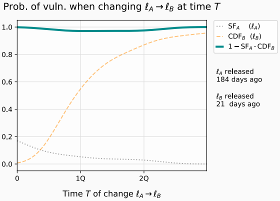


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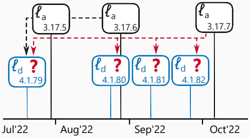


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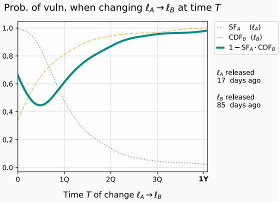


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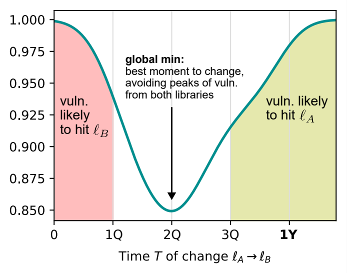


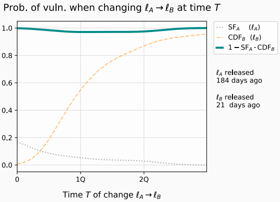


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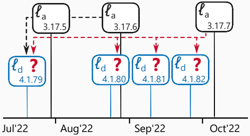


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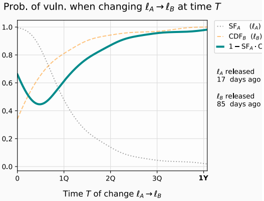


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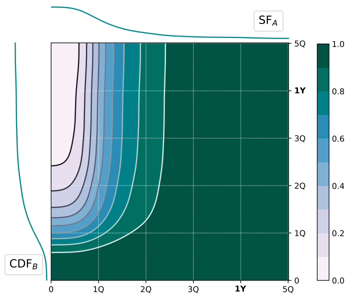


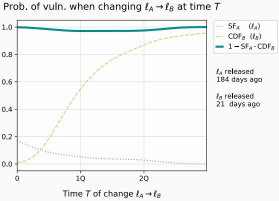


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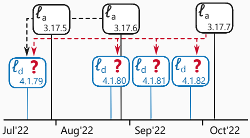


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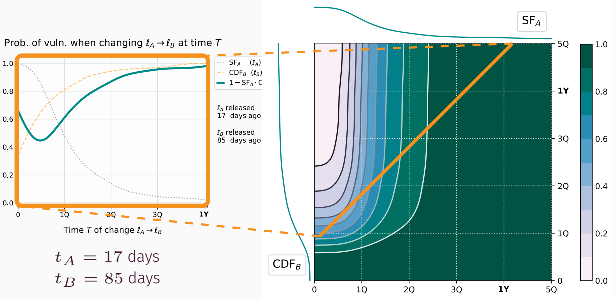


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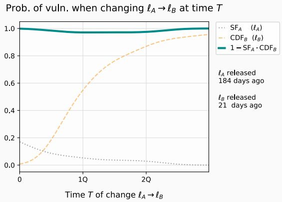


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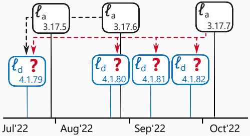


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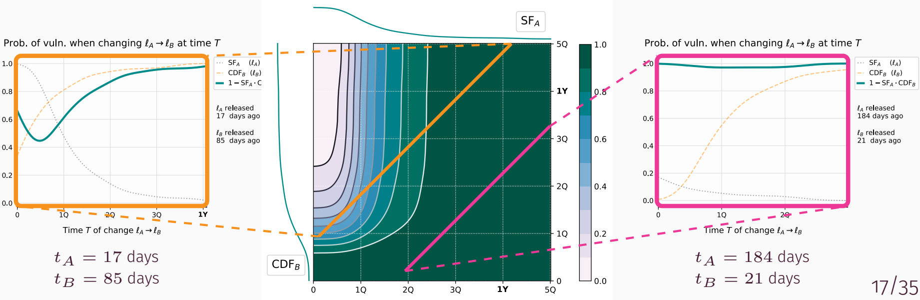


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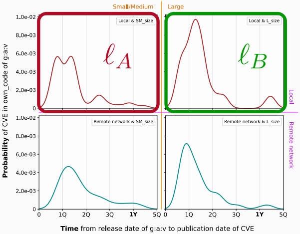

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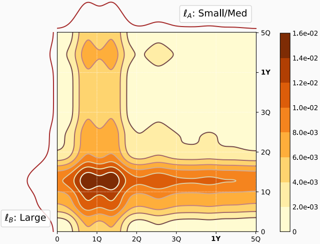


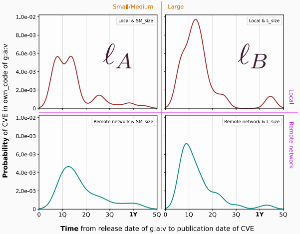

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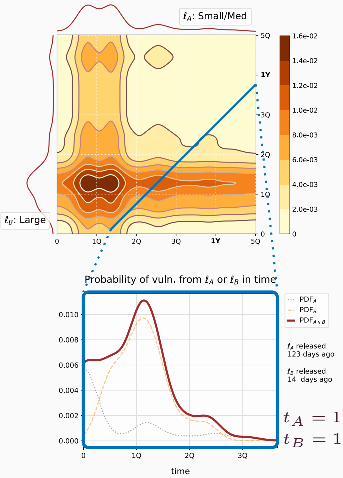


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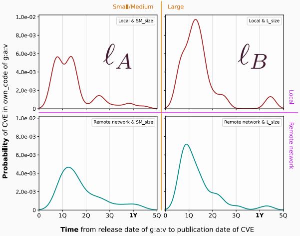

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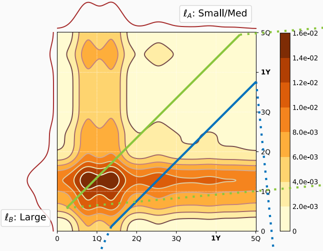


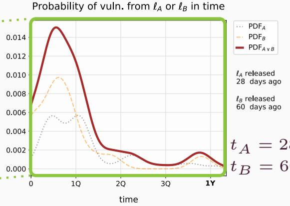


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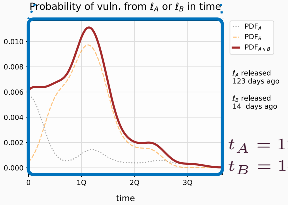


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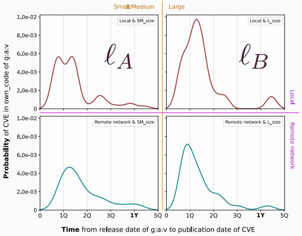

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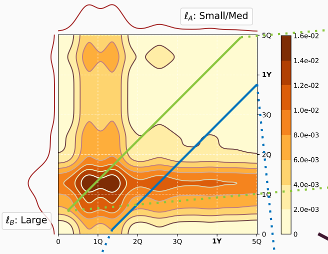


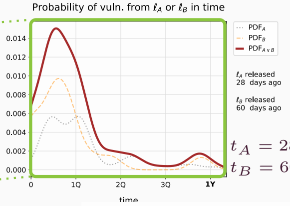


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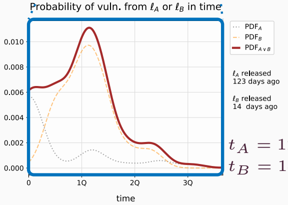


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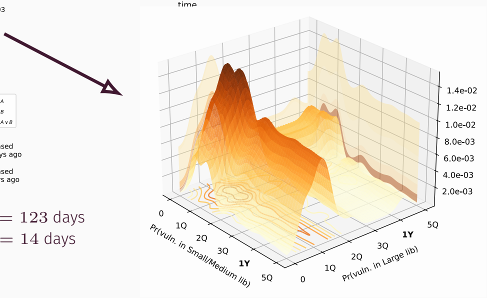

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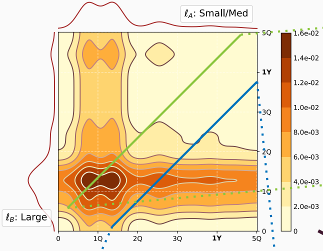


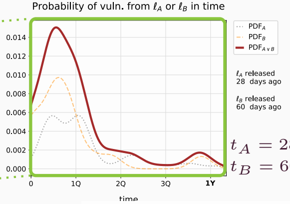


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Nice for **2** dependencies!

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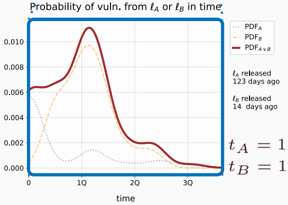


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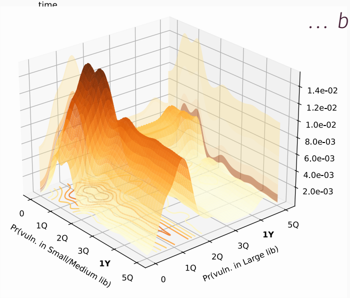

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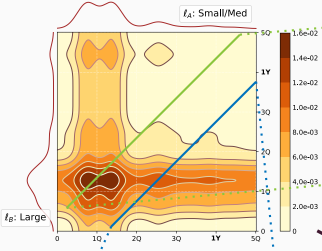


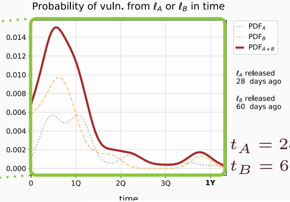


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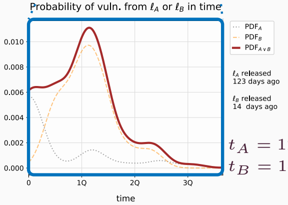


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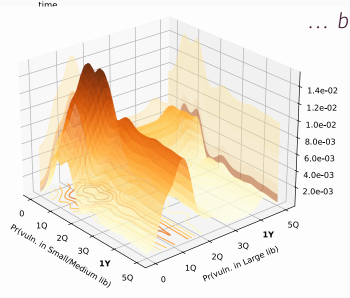


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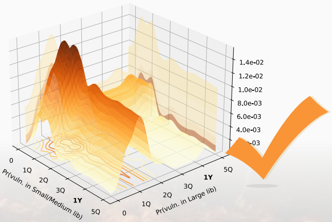
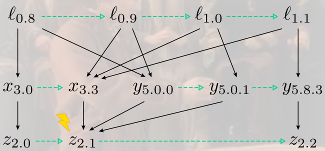
**TDTs!**

# Forecast model



CVE root-lib PDFs




Time Dependency Trees

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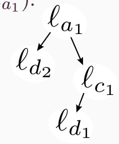
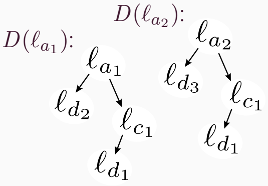
Dependency Trees in time

$D(\ell_{a_1})$:



# Time Dependency Trees

Dependency Trees in time



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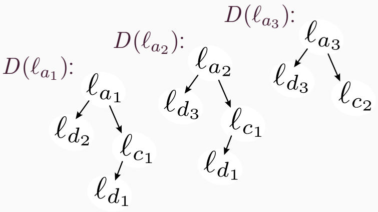
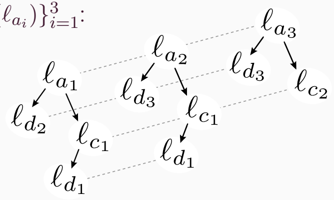


# Time Dependency Trees

Dependency Trees in time

$\{D(\ell_{a_i})\}_{i=1}^{3}$:



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## Dependency Trees in time

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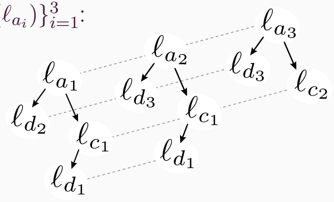
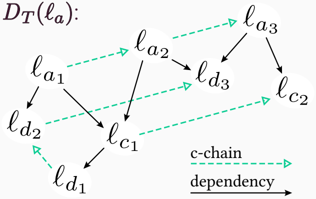



## Time Dependency Tree

$D_T(\ell_a)$:



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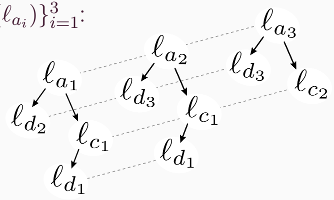


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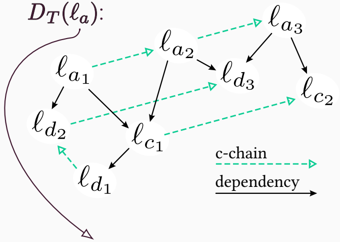
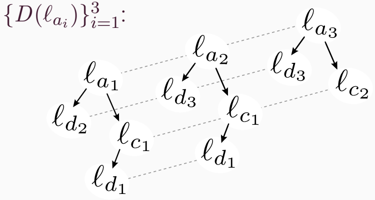


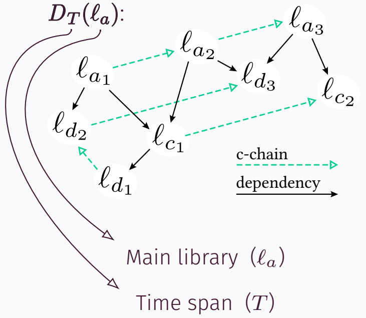

Main library ($\ell_a$)

# Time Dependency Trees

Dependency Trees in time




Time Dependency Tree



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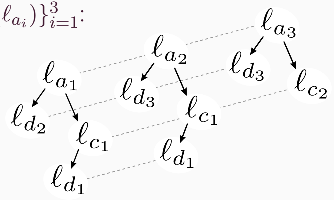
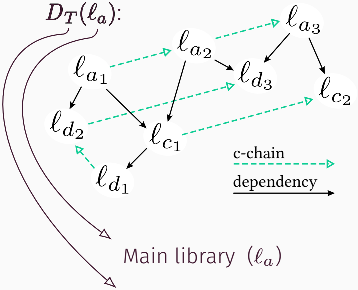



$D_t(\ell_a) = D(\ell_{a_1})$
for any time point $t \in T$
after the release of $\ell_{a_1}$ and
before the release of $\ell_{a_2}$

Time Dependency Tree

$D_T(\ell_a)$:




Main library $(\ell_a)$

Time span $(T)$

# Properties of TDT $D_T(\ell)$

- Minimal graph representation (no lib-version repetition)

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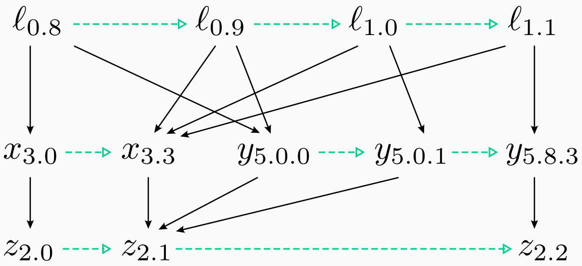
# SPoF in time and dependencies

My personal project uses $\ell_{1.0}$



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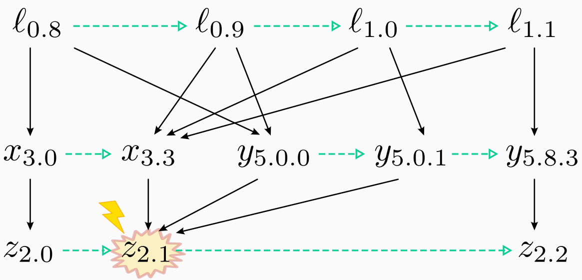

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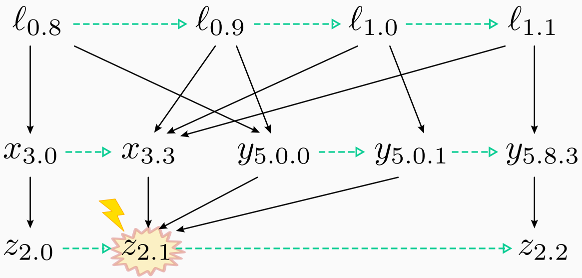


Should I downgrade to $\ell_{0.9}$ or upgrade to $\ell_{1.1}$?

# Properties of TDT $D_T(\ell)$

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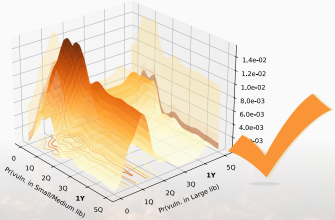
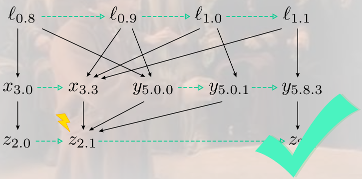
- Can measure health/risk of development environment

# Forecast model



CVE root-lib PDFs




Time Dependency Trees

# Conclusions

# Some things done

- Time Dependency Trees

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  - Aggregate dependency and code-evolution data

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# Some things done

- Time Dependency Trees
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  - Discriminate per type of library (security-relevant props.)

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- Time Dependency Trees
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  - Express time from library release to CVE publication
  - Discriminate per type of library (security-relevant props.)
  - Base information for probability forecasting

# Some things done

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to be

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- Other metrics to clusterise libraries for PDF-fitting

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- c-chains polution by CVE

# Questions?

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# Forecasting software vulnerabilities

## Probability Density Functions and Time Dependency Trees

C.E. Budde R. Paramitha F. Massacci

14th March 2024

ProSVED final event symposium