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Vector Space Embeddings and Data Maps for Cyber Defense

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Tutte Institute for Mathematics and Computing

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Cyber Defense Data

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What is cyber defense?

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Detect threats to

Confidentiality

Integrity

Availability

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Gather forensic evidence of incidents

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Requires data and infrastructure monitoring: telemetry

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Telemetry analysis:
Know the infrastructure
Retrace malicious activity

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Which “the telemetry”

Process command lines
IP traffic flows
Event logs
Malware binaries
Operating system events
etc.

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Which “the telemetry”

Process command lines

IP traffic flows

Event logs

Malware binaries

Operating system events

etc.

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ACME3 data

24 hosts, 16 days
~137,847 command lines
~31,000 unique command lines

```
c:\windows\system32\conhost.exe 0xffffffff -forcev1
c:\windows\system32\mousocoreworker.exe -embedding
c:\program files (x86)\microsoft\edgeupdate\microsoftedgeupdate.exe /ua /installsource scheduler
c:\windows\system32\svchost.exe -k netsvcs -p -s netsetupsvc
c:\windows\system32\taskhostw.exe
....

c:\programdata\microsoft\windows defender\platform\4.18.23090.2008-0\mpcmdrun.exe -idletask -taskname wdcleanup
c:\programdata\microsoft\windows defender\platform\4.18.23090.2008-0\mpcmdrun.exe -idletask -taskname wdverification
c:\windows\system32\taskhostw.exe keyroaming
c:\windows\system32\fontdrvhost.exe
c:\windows\system32\openssh\sshd.exe -r
c:\windows\system32\openssh\sshd.exe -y
c:\windows\system32\cmd.exe
C:\windows\system32\conhost.exe
....
```

https://gdo168.llnl.gov/data/ACME-2023

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Key constraint: no label

Unsupervised analysis:
examine patterns of similarity

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Every approach is a lense

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Every representation tells a story

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All ~~models~~ Lenses are wrong,
Some are useful

George Box

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A useful lense provides insight and helps with labelling

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VECTORIZERS

UNIFORM MANIFOLD UMAP APPROXIMATION & PROJECTION

TNT THIS NOT THAT and DATAMAPPLOT

scikit learn

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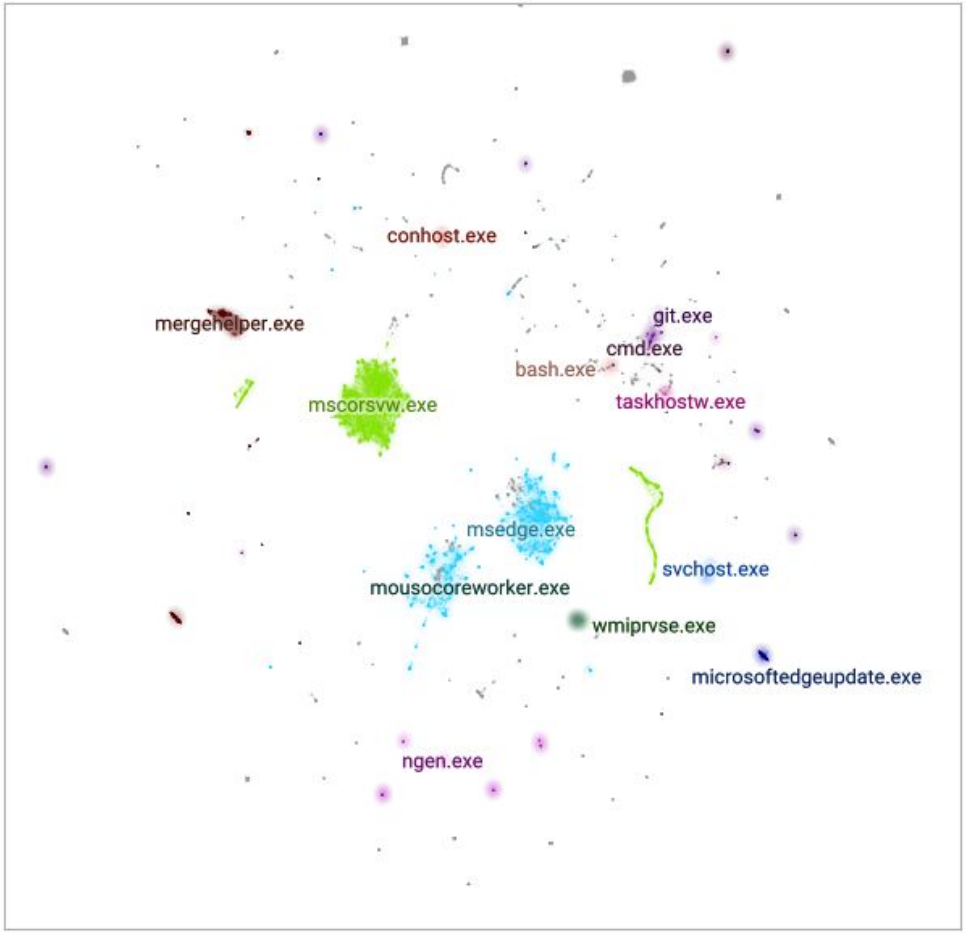
Data map of processes



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Building lenses

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VECTORIZERS

UNIFORM MANIFOLD UMAP APPROXIMATION & PROJECTION

TNT THIS NOT THAT and DATAMAPPLOT

scikit learn

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OpenAI

cohere

Hugging Face

```
[ 0.0021  0.0246 -0.0134  0.0343 ... -0.0103 -0.0008  0.0047  0.0363]
[ 0.0068  0.0098 -0.0079 -0.0006 ... -0.0018  0.0361  0.002   0.0045]
[ 0.021   0.0239  0.0024  0.0087 ... -0.0167 -0.0309 -0.0144 -0.0045]
[-0.0082  0.0234 -0.0166  0.0078 ...  0.0375 -0.03    0.0367 -0.0141]
[-0.0535 -0.002  -0.0141 -0.0198 ... -0.0071 -0.0074  0.0042  0.0034]
[ 0.0233  0.0273 -0.0139  0.0361 ...  0.0036 -0.0334  0.041   0.0253]
[-0.002   0.0076  0.0048 -0.0299 ...  0.0057  0.0089  0.015   0.0169]
[ 0.0066  0.0171 -0.0076 -0.0234 ... -0.0065 -0.0082 -0.0097  0.0065]
[-0.0112  0.0172  0.0051 -0.0432 ...  0.028  -0.0114  0.0481 -0.0051]
[-0.0003  0.0093 -0.0221  0.0302 ... -0.015  -0.0136  0.0012 -0.0205]
[-0.0183  0.011   0.0172 -0.0162 ... -0.0168 -0.003   0.0287  0.0069]
[ 0.0392  0.0106 -0.0003  0.0082 ... -0.0287  0.0081  0.0042  0.026 ]
[-0.0155  0.0163 -0.0126 -0.0035 ...  0.0233  0.0009 -0.028   0.0179]
[-0.0101  0.0118 -0.0006 -0.0225 ... -0.0283 -0.0076  0.0293  0.0114]
[-0.0341  0.0303 -0.0015 -0.0195 ... -0.0459 -0.0501  0.0211  0.0116]
[ 0.0011  0.0125  0.0176 -0.0349 ... -0.0147  0.0016  0.035   0.0386]
[-0.0329  0.0044 -0.0127 -0.0076 ...  0.     -0.008   0.0692 -0.0044]
[-0.0039  0.0214 -0.0231  0.0164 ...  0.0124 -0.005   0.0266 -0.0446]
[-0.0173  0.0227  0.0188 -0.0349 ... -0.0235 -0.0243  0.004  -0.0072]
[-0.0254  0.0279 -0.0279  0.0003 ... -0.0189 -0.0109  0.032   0.0067]
[-0.0196  0.0046  0.0117 -0.0074 ... -0.0047  0.0076  0.0297  0.0075]
[-0.0255  0.0056  0.0052  0.0046 ... -0.0005  0.0038  0.0074  0.0015]
[-0.004   0.0218 -0.024   0.0136 ... -0.0122  0.0158  0.001   0.0139]
[-0.0319  0.0259  0.0051  0.0245 ... -0.0092 -0.0121 -0.0023 -0.026 ]
[ 0.0046  0.0147 -0.033  -0.0037 ... -0.0223  0.0213  0.0352 -0.0205]
[-0.0097  0.0017 -0.0027 -0.0412 ... -0.0039 -0.0041  0.0132  0.0119]
[-0.0043  0.0303 -0.0093 -0.0129 ... -0.0054  0.0176  0.0062  0.011 ]
[ 0.0032 -0.0213 -0.0307 -0.0157 ... -0.0327 -0.007   0.0099 -0.0053]
[ 0.0171 -0.009   0.0408 -0.0232 ... -0.0122  0.0043 -0.0433  0.0164]
[-0.0029  0.0067 -0.0018 -0.0205 ... -0.017   0.0101  0.0083 -0.0049]
[-0.0028  0.0106  0.0173  0.0014 ... -0.0097 -0.0186  0.0058 -0.0031]
[-0.0089  0.0277 -0.014  -0.0308 ...  0.0001  0.0137 -0.0063 -0.0169]
[-0.0099 -0.0112 -0.0366 -0.0169 ... -0.0178  0.0003  0.0122 -0.0082]
[-0.0049  0.0123 -0.0125 -0.0267 ... -0.0284 -0.0124 -0.0069 -0.0086]
[-0.0206  0.0202  0.0198  0.002  ...  0.0108  0.0031  0.0146 -0.0195]
[ 0.0132 -0.004  -0.0075  0.006  ... -0.0001 -0.0082  0.0678 -0.0091]
[-0.0249  0.0234  0.0223 -0.0028 ...  0.0049 -0.0101  0.0248  0.0184]
[-0.0414  0.0088 -0.0256  0.0013 ... -0.0255 -0.0297  0.0186  0.0312]
[ 0.0086  0.0071 -0.0162 -0.0069 ... -0.0312  0.0254  0.0032 -0.0135]
[-0.0015  0.0054  0.0004 -0.0261 ...  0.0167 -0.0128 -0.0093  0.0118]
[ 0.0141 -0.0039  0.0078  0.0028 ... -0.0111 -0.0412 -0.0066 -0.0232]
[-0.0002  0.0219 -0.0078  0.0075 ... -0.0385  0.0036 -0.0074 -0.0108]
[-0.0191 -0.003  -0.0061 -0.0098 ... -0.0053 -0.0144  0.0156  0.0071]
[-0.0152  0.0059 -0.     -0.0005 ... -0.0059  0.0006 -0.0383  0.018 ]
[-0.0209  0.0095 -0.0229 -0.0163 ... -0.0211  0.0104 -0.0013  0.006 ]
[ 0.0083  0.0059 -0.0371 -0.0072 ...  0.0056 -0.0122  0.022  -0.0132]
[-0.0393  0.0132 -0.0268 -0.0057 ...  0.0072 -0.0173  0.0238  0.0131]
[-0.0213 -0.0035  0.0078 -0.0224 ...  0.0013 -0.0067 -0.0158 -0.0085]
[-0.0371 -0.019  -0.0137 -0.0019 ... -0.0052 -0.037   0.0164  0.0238]
[ 0.0252 -0.017   0.0041  0.0001 ... -0.0062 -0.0307 -0.0372  0.002 ]
[-0.0395  0.0227 -0.0322 -0.0335 ... -0.0503  0.0124 -0.021  -0.0249]
```

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Tools to vectorize other types of data

Process command lines
IP Traffic Flows
Event logs
Malware Binaries
etc...

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Text to vectors: bag of words

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Parse command lines into tokens

cmdline	tokens	num
"c:\windows\system32\consent.exe" 8364 316 00000225c123a720	["c:\windows\system32\consent.exe", 8364, 316, 00000225c123a720]	4
"c:\windows\syswow64\msiexec.exe" -embedding dabb2a6d532491a1295e2c3d16e9fdfd	["c:\windows\syswow64\msiexec.exe", -embedding, dabb2a6d532491a1295e2c3d16e9fdfd]	3
"c:\windows\system32\consent.exe" 7040 288 0000019ec8c2a540	["c:\windows\system32\consent.exe", 7040, 288, 0000019ec8c2a540]	4
"c:\windows\system32\curl.exe" --help	["c:\windows\system32\curl.exe", --help]	2
"c:\windows\system32\consent.exe" 1640 318 00000204e5430040	["c:\windows\system32\consent.exe", 1640, 318, 00000204e5430040]	4
"c:\windows\system32\svchost.exe" -k wsappx -p -s appxsvc	["c:\windows\system32\svchost.exe", -k, wsappx, -p, -s, appxsvc]	6
"c:\windows\system32\ping.exe" acme-dc1.acme.com	["c:\windows\system32\ping.exe", acme-dc1.acme.com]	2
"c:\windows\system32\sihclient.exe" /cv sq9lrmw140ena5nxthiida.0.1	["c:\windows\system32\sihclient.exe", /cv, sq9lrmw140ena5nxthiida.0.1]	3
"c:\program files\git\usr\bin\ls.exe" -f --color=auto --show-control-chars 1277	["c:\program files\git\usr\bin\ls.exe", -f, --color=auto, --show-control-chars, 1277]	5
"c:\users\user10\downloads\visualstudiosetup.exe"	["c:\users\user10\downloads\visualstudiosetup.exe"]	1
"c:\windows\system32\svchost.exe" -k unistacksvcgroup	["c:\windows\system32\svchost.exe", -k, unistacksvcgroup]	3
"c:\windows\system32\sihclient.exe" /cv cxixvz5jlemri9ydvjhbea.0.1	["c:\windows\system32\sihclient.exe", /cv, cxixvz5jlemri9ydvjhbea.0.1]	3
"c:\windows\system32\systeminfo.exe" /?	["c:\windows\system32\systeminfo.exe", /?]	2
"c:\program files\git\usr\bin\ls.exe" -f --color=auto --show-control-chars 953	["c:\program files\git\usr\bin\ls.exe", -f, --color=auto, --show-control-chars, 953]	5
"c:\windows\system32\wbem\wmic.exe" product list brief	["c:\windows\system32\wbem\wmic.exe", product, list, brief]	4

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```
%%time
vz_ngram = vz.NgramVectorizer().fit(cmdlines_tokenized.tolist())
cmdlines_tc = vz_ngram._train_matrix.tocsr()
cmdlines_tc
```

```
CPU times: user 771 ms, sys: 35.8 ms, total: 807 ms
Wall time: 812 ms
```

```
<31029x20887 sparse matrix of type '<class 'numpy.float32'>'
        with 236570 stored elements in Compressed Sparse Row format>
```

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Bag of words: vectorize by counting tokens

tokens	"c:\windows\system32\svchost.exe"	-k	-p	-s	appxsvc	unistacksvcgroup	waasmedicsvc	wersvcgroup	wsappx	wusvcs
cmdline										
"c:\windows\system32\svchost.exe" -k unistacksvcgroup	1.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
"c:\windows\system32\svchost.exe" -k wersvcgroup	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
"c:\windows\system32\svchost.exe" -k wsappx -p -s appxsvc	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	1.0	0.0
"c:\windows\system32\svchost.exe" -k wusvcs -p -s waasmedicsvc	1.0	1.0	1.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0

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Information weight transform: downweight tokens with low similarity information contribution

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```
cmdlines_iwt = vzt.InformationWeightTransformer().fit_transform(cmdlines_mnom)
cmdlines_iwt
```

```
<31029x20907 sparse matrix of type '<class 'numpy.float64'>'
        with 259822 stored elements in Compressed Sparse Row format>
```

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Classical TF-IDF

$$\mathsf{IDF}(t) = \log\left(\frac{|D|}{|\{d \in D : t \in d\}|}\right)$$

Information Weight

$$\mathsf{Info}(t) = \sum_{d \in D} P_t(d) \log\left(\frac{P_t(d)}{Q(d)}\right)$$

where

$$P_t(d) = \frac{f_{t,d}}{\sum_{d \in D} f_{t,d}} \qquad Q(d) = \frac{|d|}{\sum_{d' \in D} |d'|}$$

An Information Theoretic Perspective of tf-idf measures, Aizawa 2003

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UNIFORM MANIFOLD

UMAP

APPROXIMATION & PROJECTION

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https://pair-code.github.io/understanding-umap/

UMAP

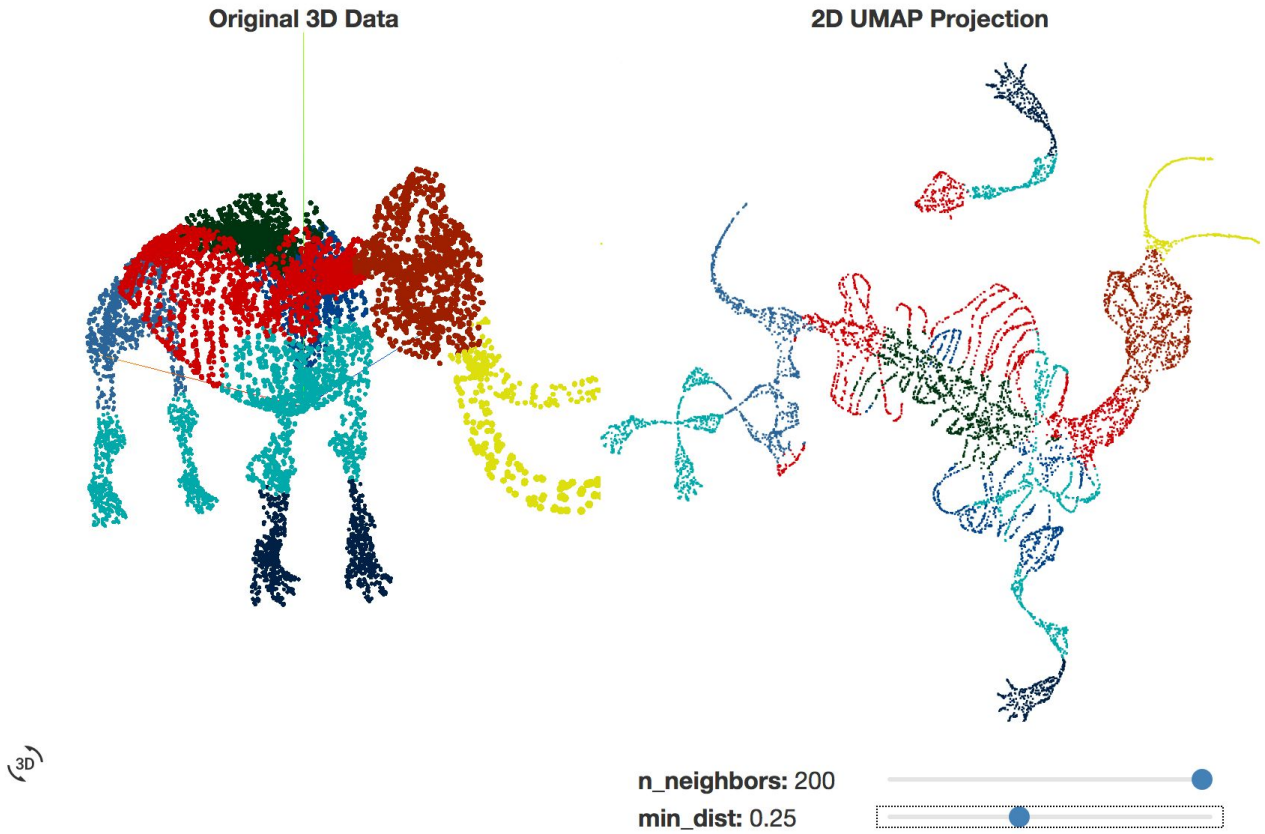

Figure 5: *UMAP projections of a 3D woolly mammoth skeleton (50,000 points) into 2 dimensions, with various settings for the* `n_neighbors` *and* `min_dist` *parameters.*

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UMAP

Reduce dimensionality while preserving local similarity structure

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UMAP

```
%%time
bagofwords_dmap = umap.UMAP(metric="hellinger").fit_transform(cmdlines_vec)
bagofwords_dmap.shape
```

```
CPU times: user 1min 50s, sys: 3.08 s, total: 1min 53s
Wall time: 19.1 s
(31029, 2)
```

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Hellinger distance

UMAP

$$d(\mathbf{x}, \mathbf{y}) = \sqrt{1 - \sum_{i=1}^{d} \sqrt{\frac{x_i, y_i}{\|\mathbf{x}\|_1 \|\mathbf{y}\|_1}}}$$

Approximated by cosine distance

$$d(\mathbf{x}, \mathbf{y}) = 1 - \sum_{i=1}^{d} \frac{x_i, y_i}{\|\mathbf{x}\|_2 \|\mathbf{y}\|_2}$$

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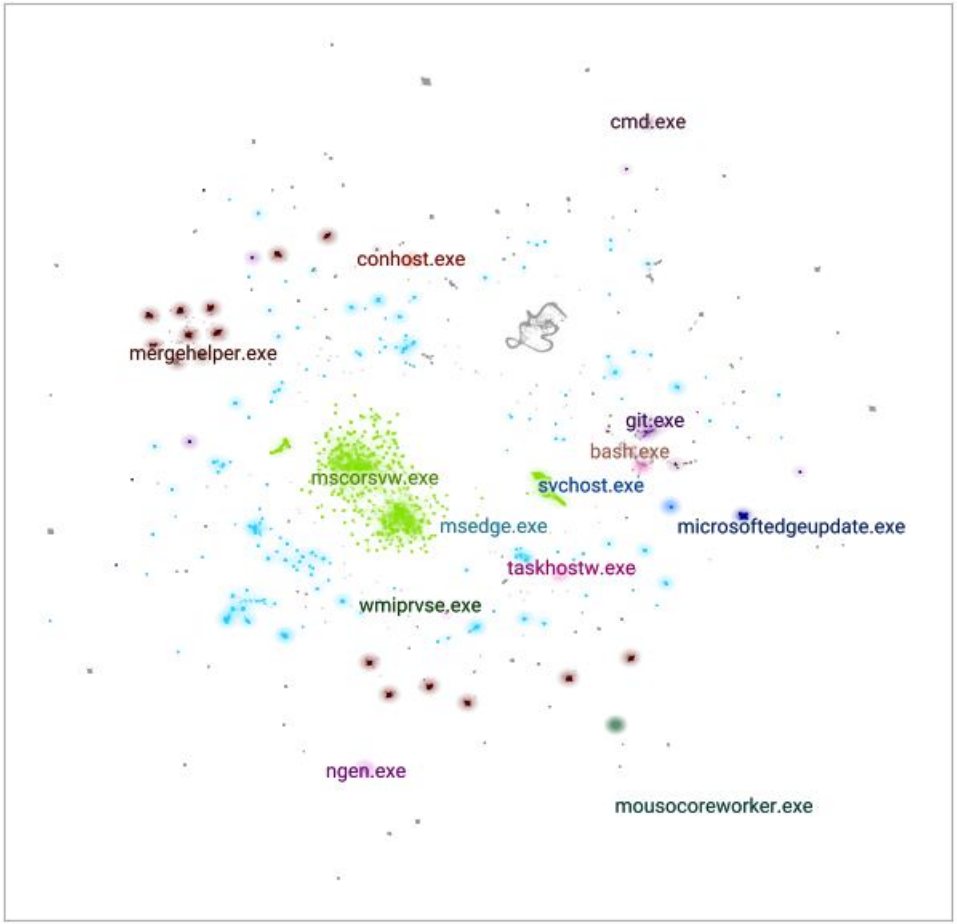
Process instances

as bags of information-reweighted parsed command line tokens



UMAP

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Tokens aren’t independent

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Command Line vectorization strategies

Bag of tokens

Discard order, count how often each word occurs

Point cloud of tokens

Optimal transport on **token vector** distributions

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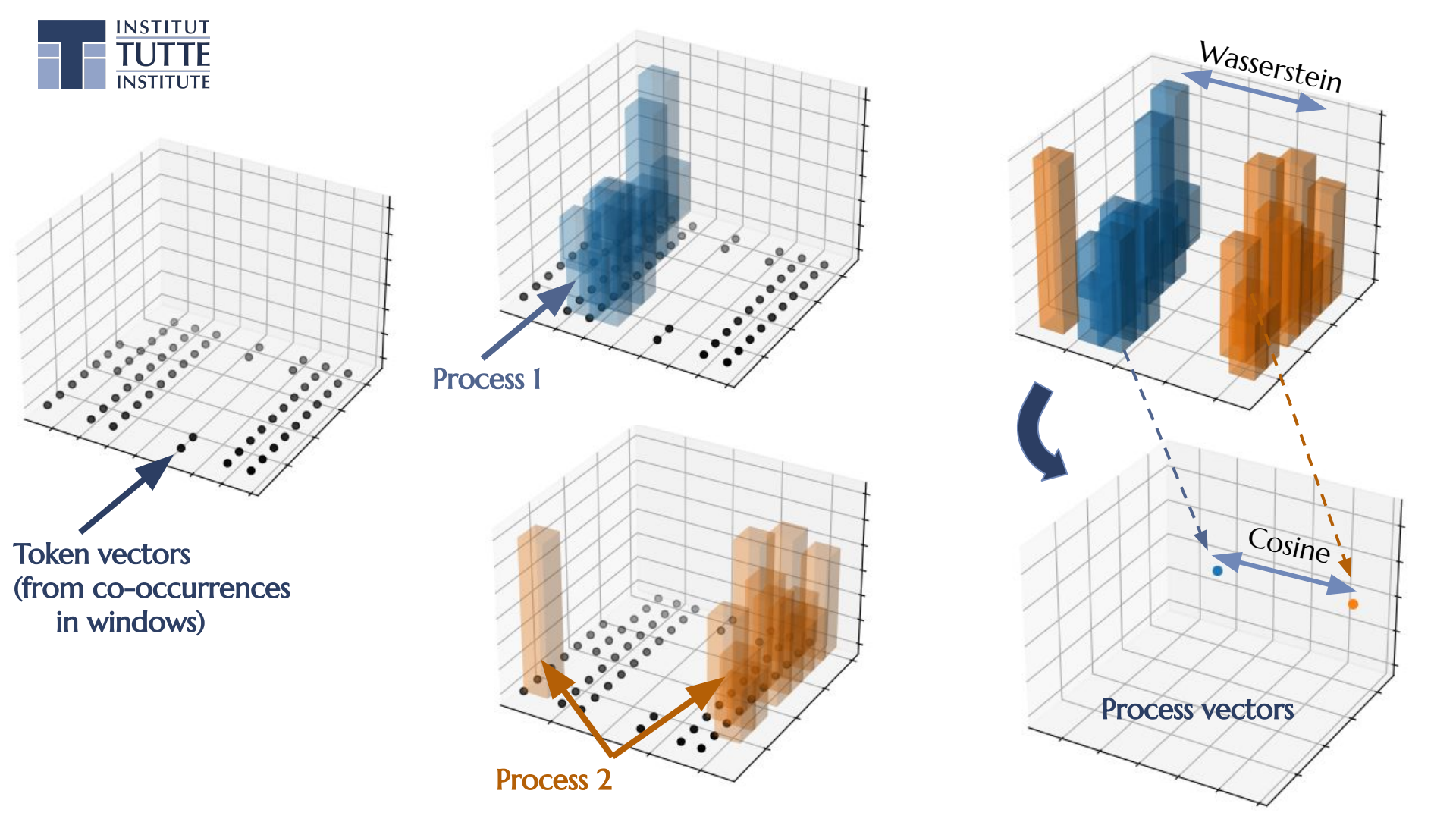
Tokens to vectors: command lines are distributions on point clouds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Token vectors
(from co-occurrences
in windows)
Process 1
Process 2
Wasserstein
Cosine
Process vectors

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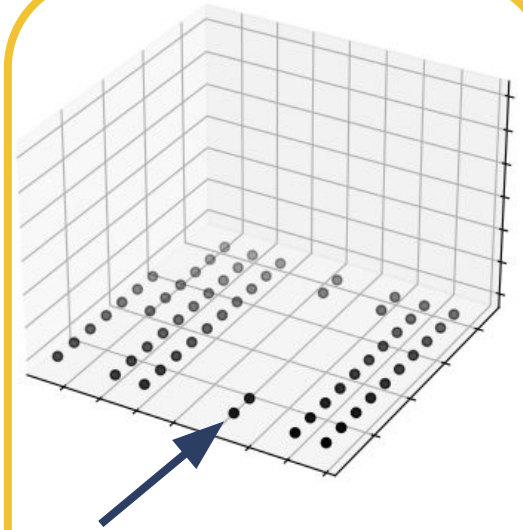
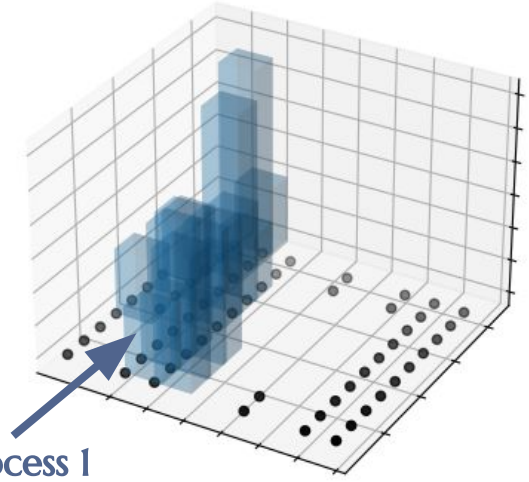
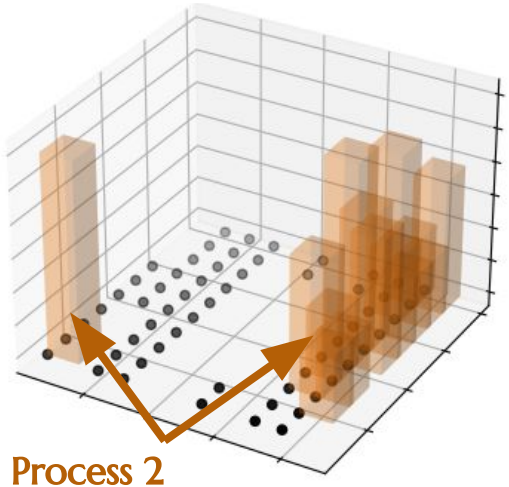


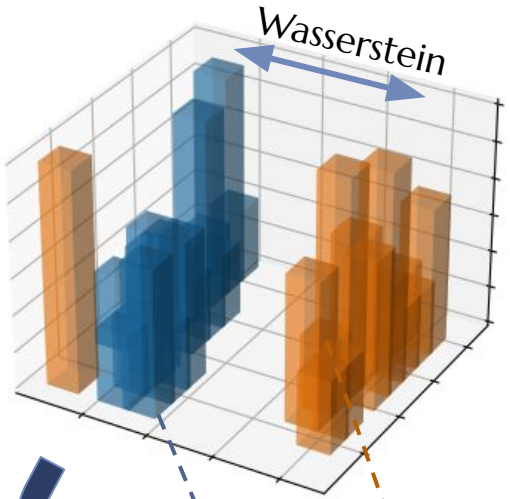
Token vectors
(from co-occurrences
in windows)

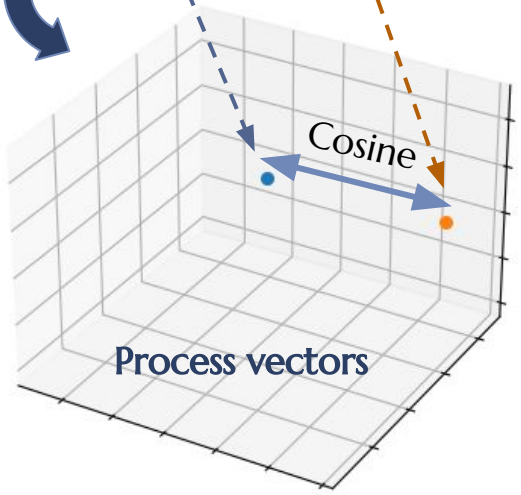


Process 1



Process 2





```
%%time
vz_cooc = vz.TokenCooccurrenceVectorizer(n_threads=os.cpu_count(), n_iter=3)\
    .fit(cmdlines_tokenized.tolist())
cooc_vec = vz_cooc.reduce_dimension(512)
cooc_vec.shape
```

```
CPU times: user 2min 1s, sys: 7.18 s, total: 2min 8s
Wall time: 25.9 s
(20887, 512)
```

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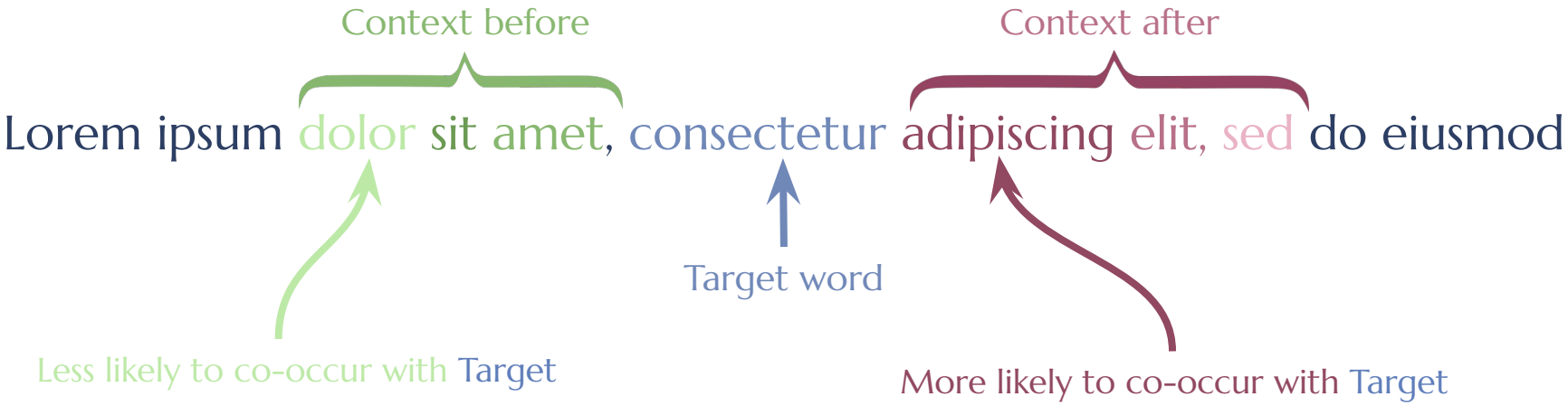
Count local cooccurrences of tokens to generate vector representation of tokens


Context before
Context after
Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod
Target word
Less likely to co-occur with Target
More likely to co-occur with Target

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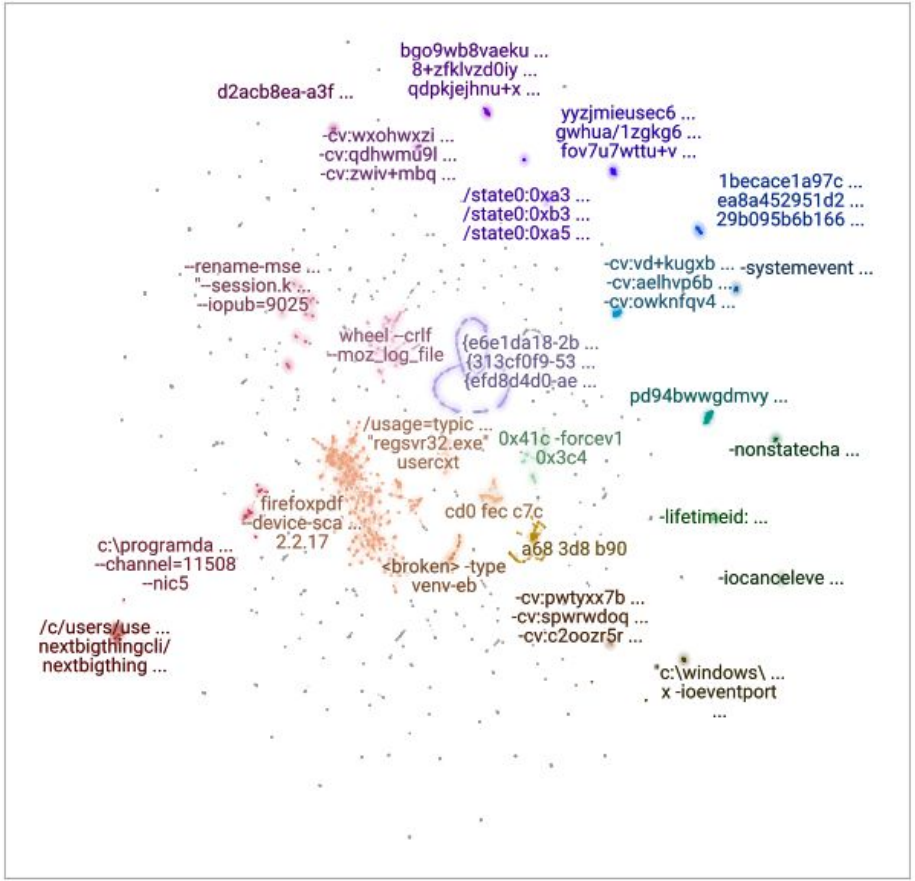
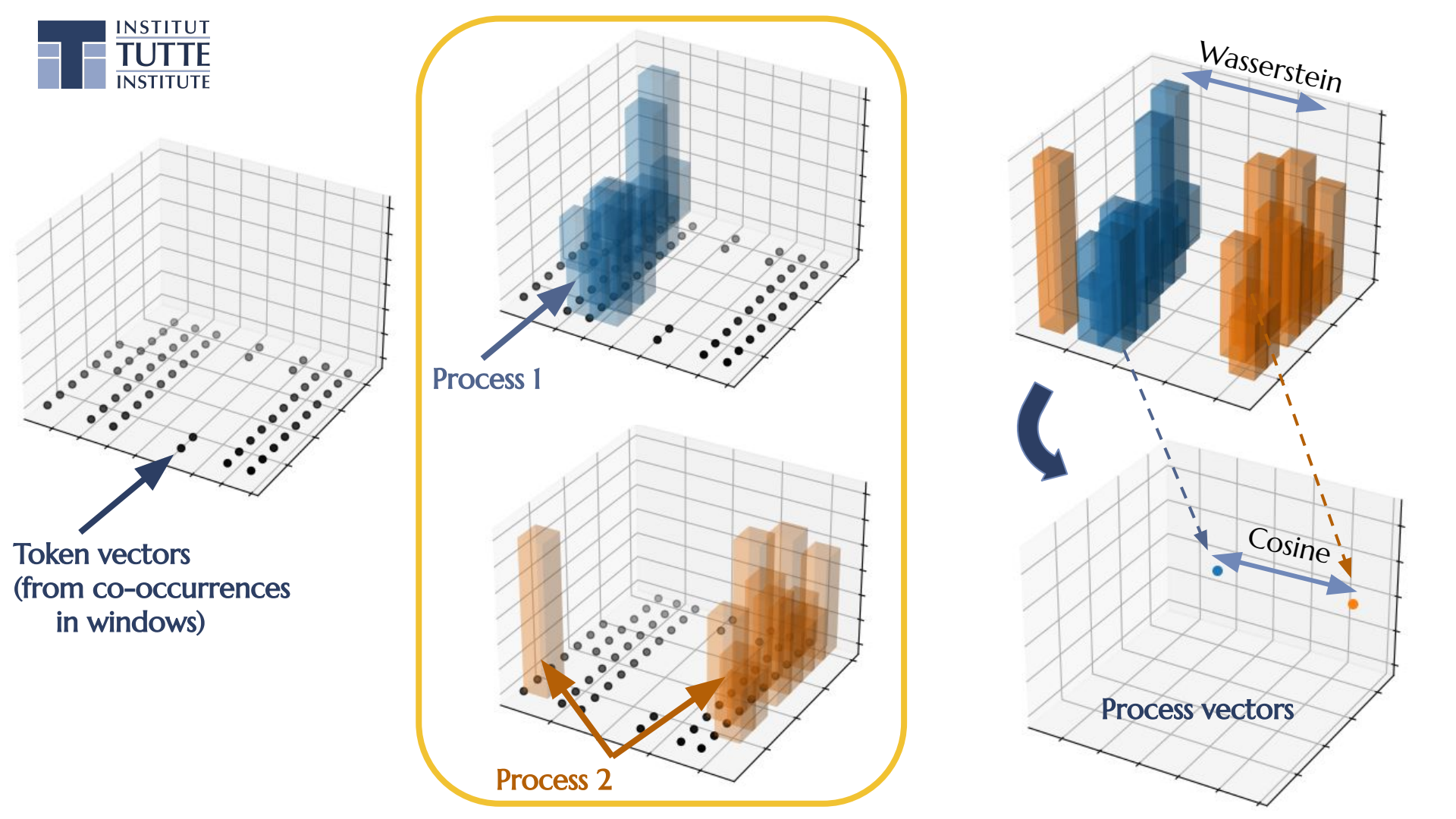
Token vectors

composed from cooccurrence with other tokens across command lines

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Token vectors
(from co-occurrences
in windows)
Process 1
Process 2
Wasserstein
Cosine
Process vectors

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Wasserstein vectorization

Via linear optimal transport

WASSERSTEIN EMBEDDING FOR GRAPH LEARNING

Soheil Kolouri* †, Navid Naderializadeh*†, Gustavo K. Rohde‡ , & Heiko Hoffmann†, 2021

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```
%%time
cmdlines_wass = vz.WassersteinVectorizer().fit_transform(cmdlines_iwt, vectors=cooc_vec)
cmdlines_wass.shape
```

```
CPU times: user 1min 33s, sys: 5.9 s, total: 1min 39s
Wall time: 17 s
(31029, 128)
```

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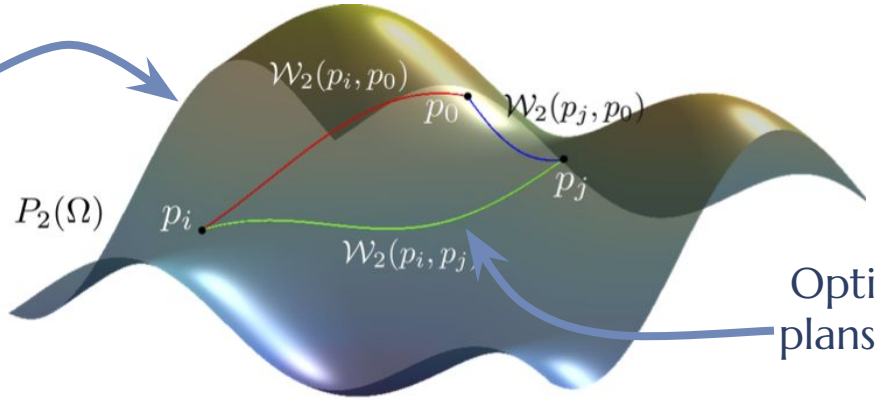
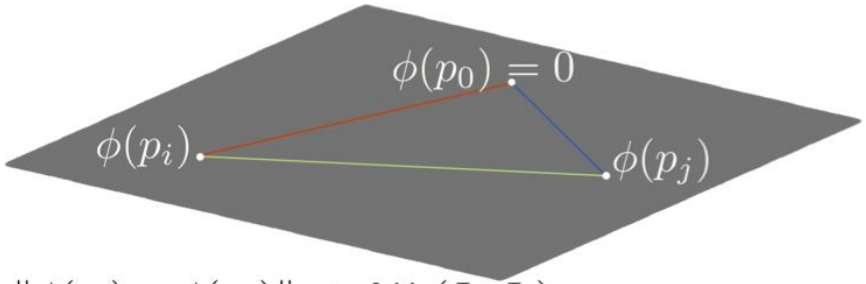
Each process is a
distribution
over a
point cloud
(of token cooccurrence vectors)

Theory

Manifold of probability distributions



Optimal transport plans are geodesics



Tangent space of the manifold at p_0

$$\|\phi(p_i) - \phi(p_j)\|_2 \approx \mathcal{W}_2(I_i, I_j)$$

$$\|\phi(p_i) - \phi(p_0)\|_2 = \|\phi(p_i)\|_2 = \mathcal{W}_2(I_0, I_i)$$

Image credit: Soheil Kolouri

Practice

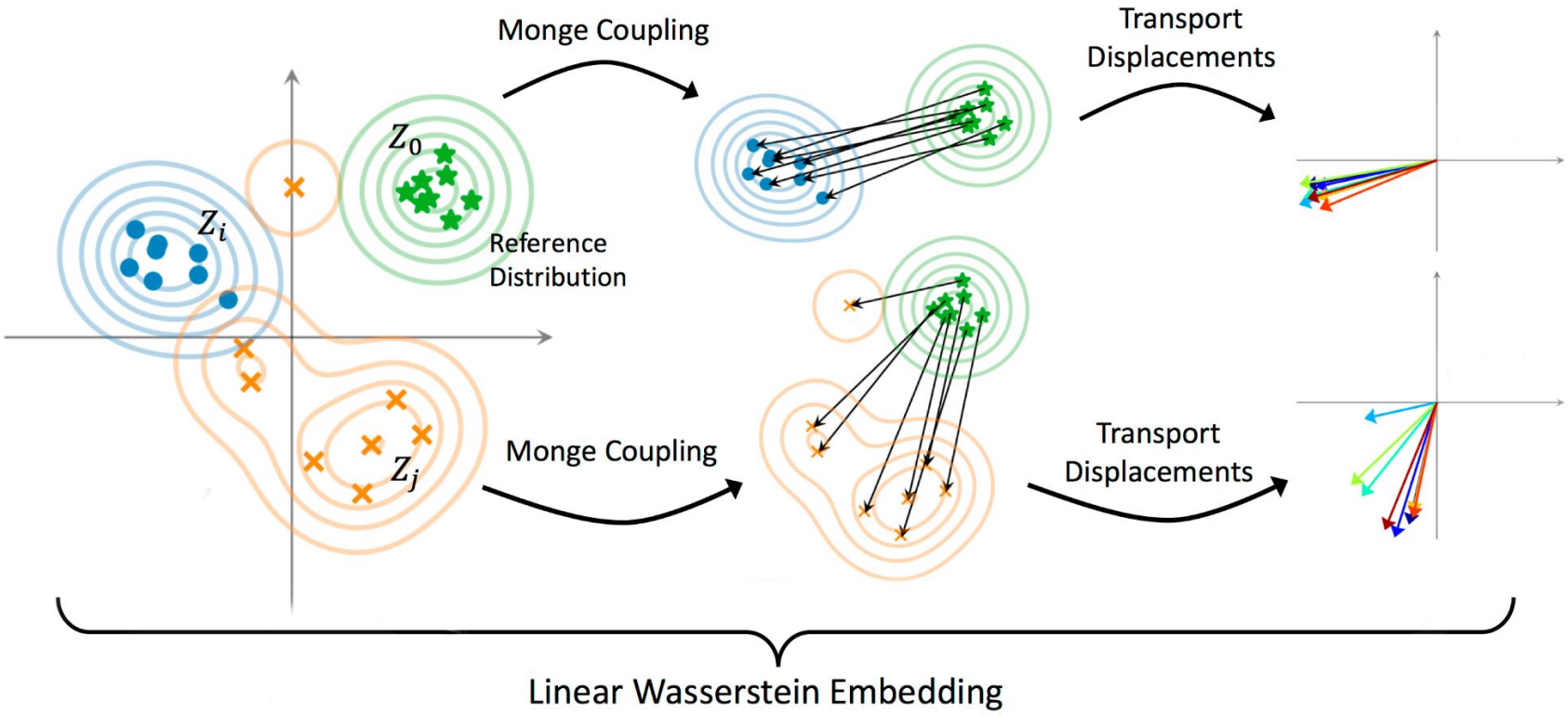


Image credit: Soheil Kolouri

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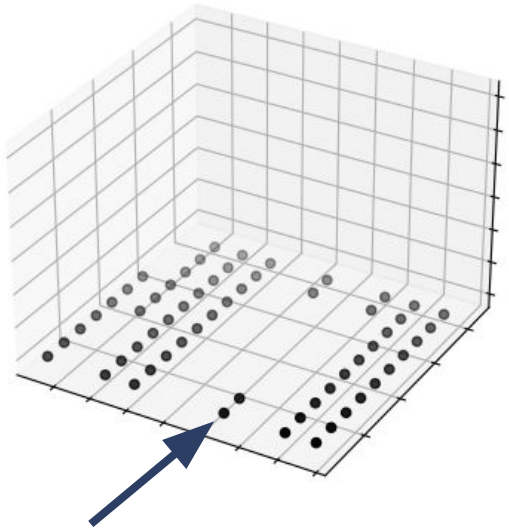
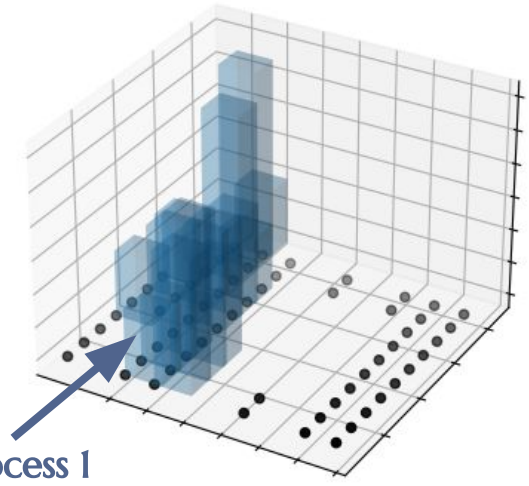
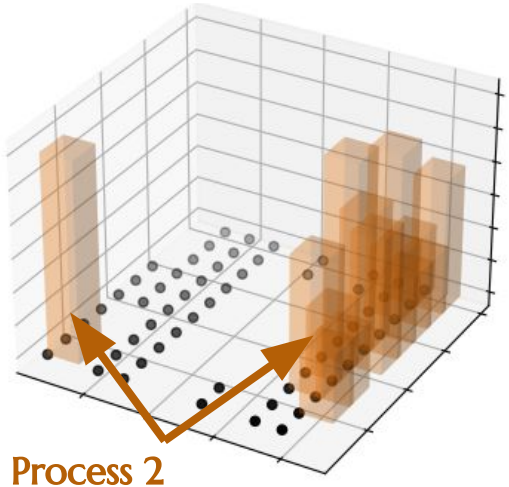


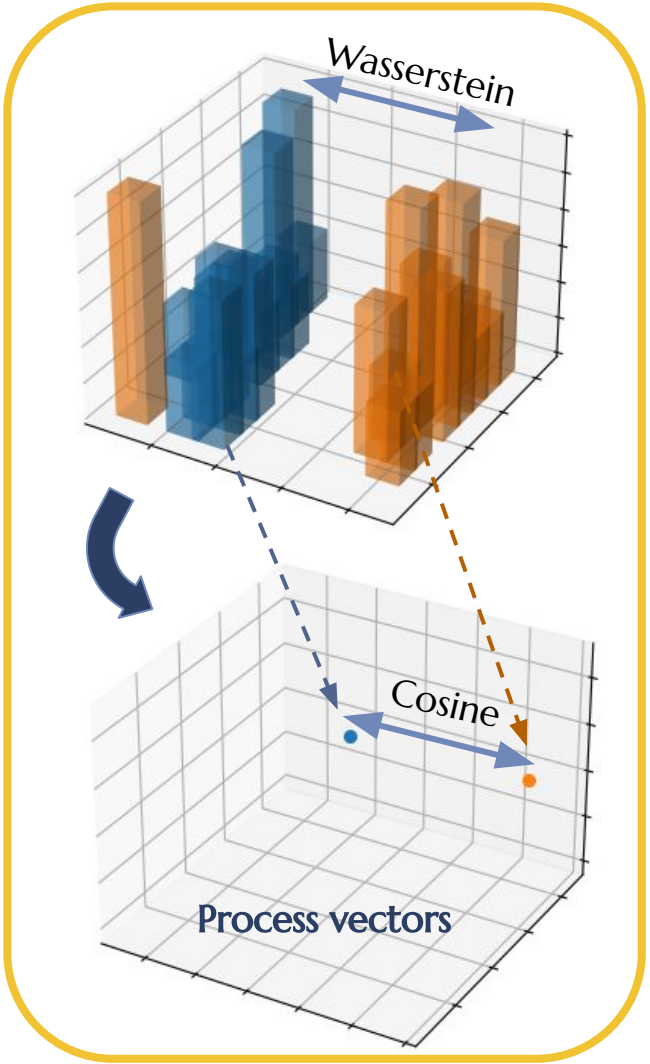
Token vectors
(from co-occurrences
in windows)



Process 1



Process 2



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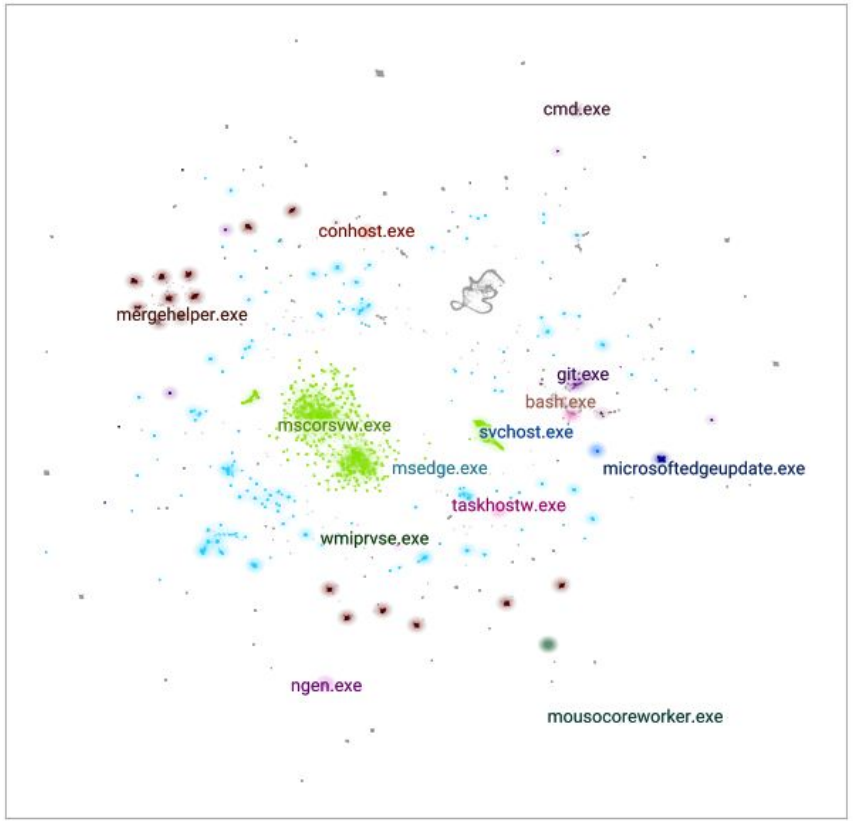
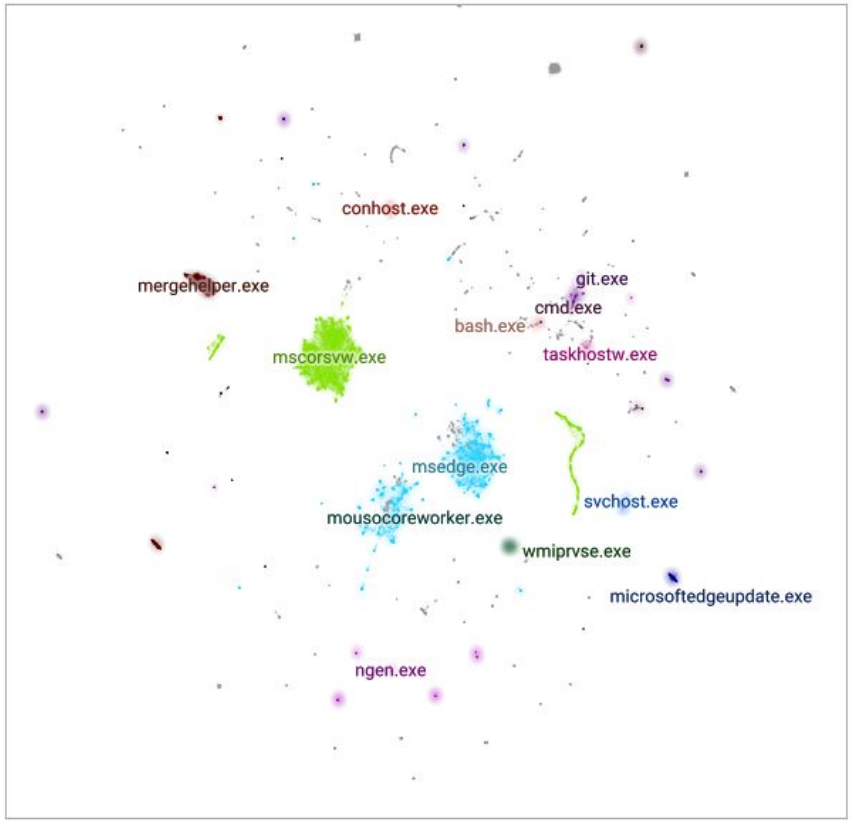
Process instances

as bags of information-reweighted parsed command line tokens



Process instances

as distributions over a cloud of command line token cooccurrence vectors



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Explore

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DataMapPlot

Easily build
attractive static and
simple interactive maps

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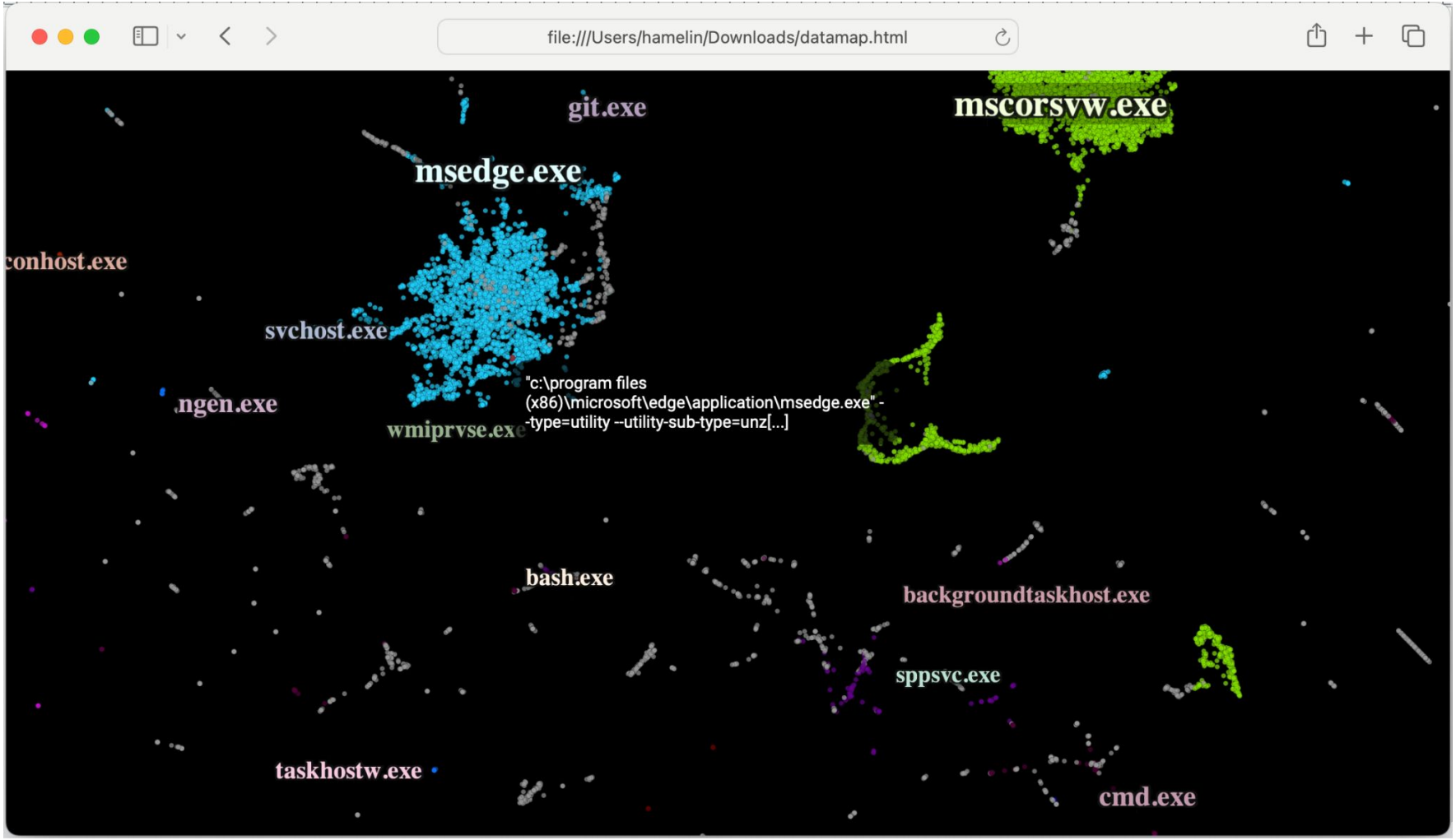
```
plot_interactive = dmp.create_interactive_plot(
    datamap,
    metadata_cmdlines["label"],
    hover_text=metadata_cmdlines["hover_text"],
    darkmode=True,
    label_color_map=label_color_map,
)
plot_interactive.save("datamap.html")
```


file:///Users/hamelin/Downloads/datamap.html
git.exe
mscorsvw.exe
msedge.exe
conhost.exe
svchost.exe
ngen.exe
wmiprvse.exe
"c:\program files (x86)\microsoft\edge\application\msedge.exe" --type=utility --utility-sub-type=unz[...]
bash.exe
backgroundtaskhost.exe
sppsvc.exe
taskhostw.exe
cmd.exe

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TNT
THIS NOT THAT

Easily build interactive map web applications

Built on top of the Panel library

Panel

```
plot = tnt.BokehPlotPane(
    xy,
    labels=metadata_processes_short["description_topK"],
    hover_text=metadata_processes_short["description"],
    width=900,
    height=900,
    show_legend=False
)
summ_common = tnt.DataSummaryPane(FeatureCommonSummarizer())
summ_common.link_to_plot(plot)
summ_ts = tnt.PlotSummaryPane(tnt.summary.plot.TimeSeriesSummarizer(
    metadata_processes_short.assign(ones=1.),
    time_column="time_first",
    count_column="ones",
    freq="12H"
))
summ_ts.link_to_plot(plot)
editor = tnt.LabelEditorWidget(labels=metadata_processes_short["description_topK"])
editor.link_to_plot(plot)
pn.Row(editor, plot, pn.Column(summ_ts, summ_common, height=900))
```

Fuller process prediction.ipy

Code

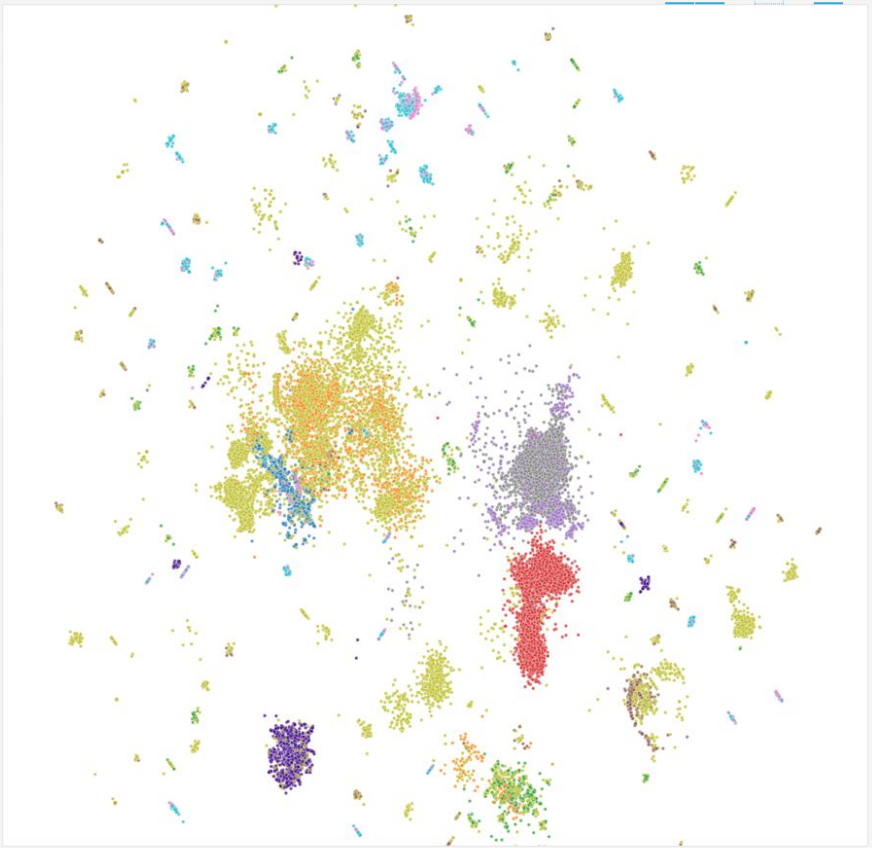
OpTC mapping

[73]:

Label Editor

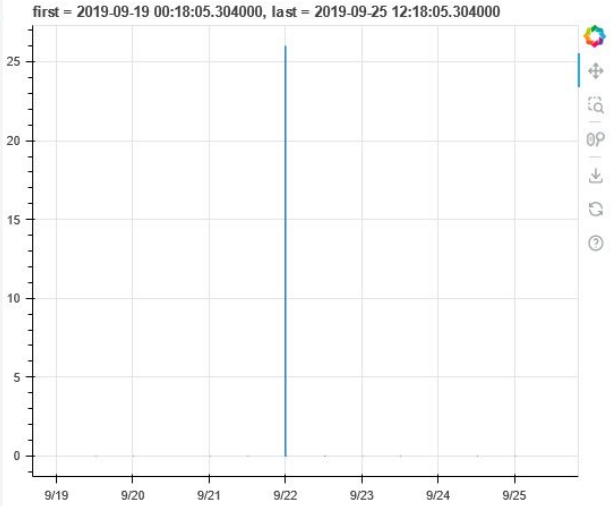
- cmd.exe /c netstat -n
- C:\Windows\system32\cmd.exe /c
- tasklist
- C:\Windows\SYSTEM32\cmd.exe /
- \Device\HarddiskVolume1\Windov
- \Device\HarddiskVolume1\Windov
- NETSTAT.EXE
- \??\C:\Windows\system32\conhost
- (other)
- netstat -n
- ping -w 2000 -n 2 127.0.0.1

New Label

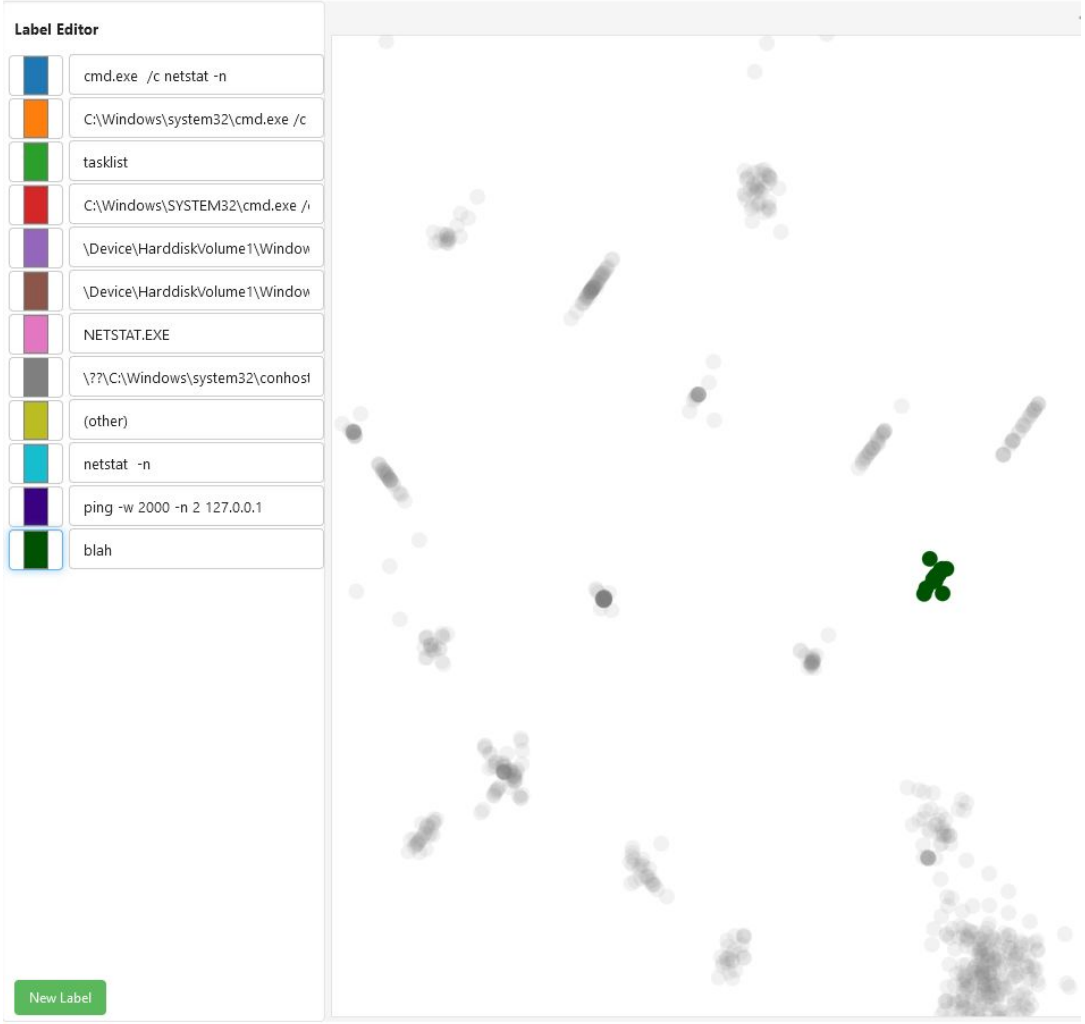


Nothing to summarize.

Nothing to summarize



	kind	value	power	frac
9	user	bantonio	5.392885	0.576923
10	domain	SYSTEMIACOM	4.924804	0.576923
11	fspath	\Device\HarddiskVolume1\Windows\system32	1.731230	0.461538
3	fspath	\Windows\System32	0.672531	0.653846
0	fspath	\Device\HarddiskVolume1\Windows	0.540241	0.807692
5	fspath	\Windows	0.301822	0.653846
2	fspath	\Windows\System32\kernel32.dll	0.125992	0.653846
1	fspath	\Device\HarddiskVolume1	0.112125	0.692308
6	fspath	\SystemRoot\System32\ntdll.dll	0.071127	0.653846
8	fspath	\Windows\System32\user32.dll	0.070582	0.653846
7	fspath	\SystemRoot\System32	0.038698	0.653846
4	fspath	\SystemRoot	0.034854	0.653846


Label Editor
cmd.exe /c netstat -n
C:\Windows\system32\cmd.exe /c
tasklist
C:\Windows\SYSTEM32\cmd.exe /
\Device\HarddiskVolume1\Windo
\Device\HarddiskVolume1\Windo
NETSTAT.EXE
\??\C:\Windows\system32\conhos
(other)
netstat -n
ping -w 2000 -n 2 127.0.0.1
blah
New Label

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scikit learn

Predict labels
or
Find clusters & anomalies

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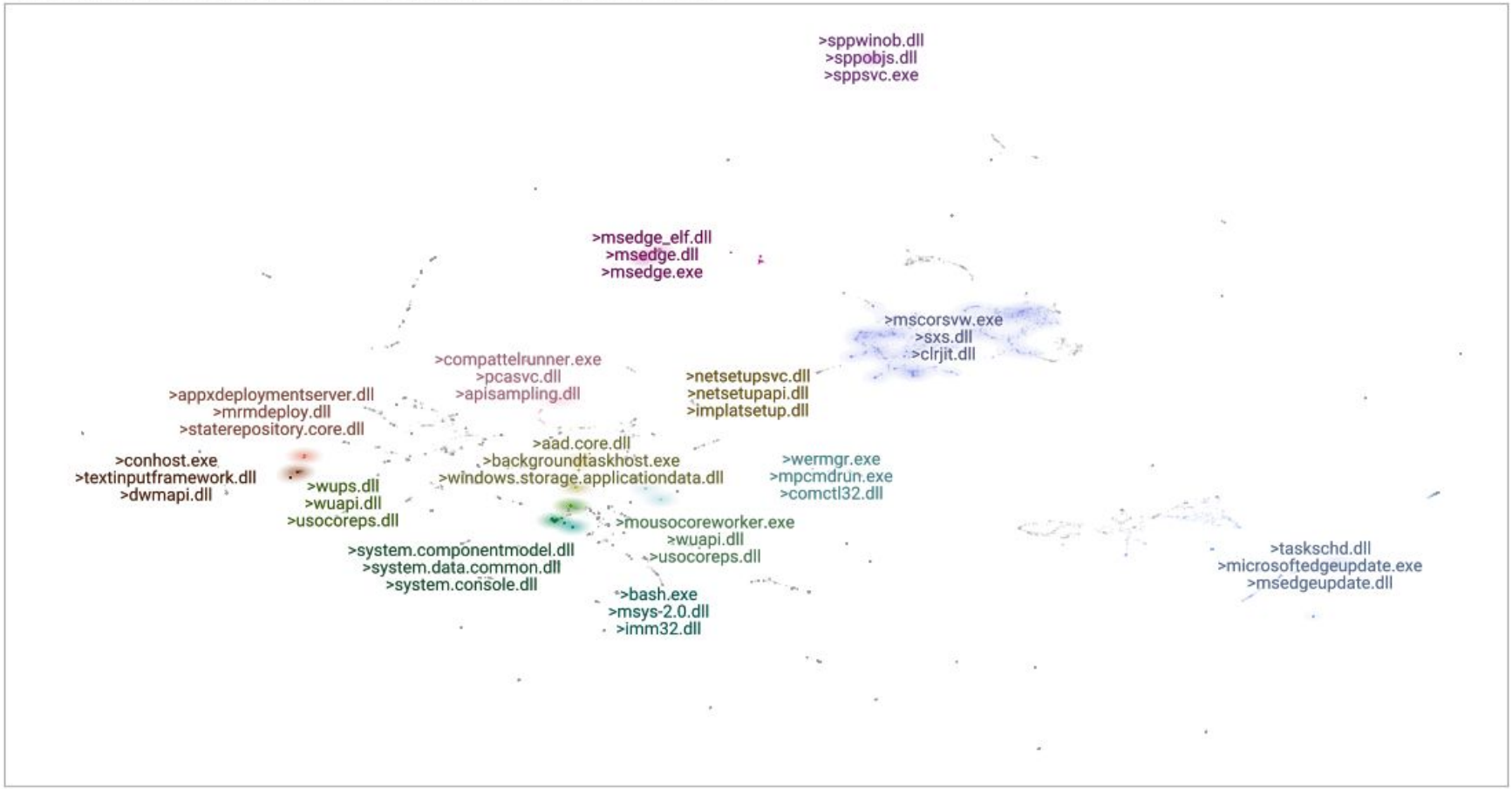
Alternate Lenses

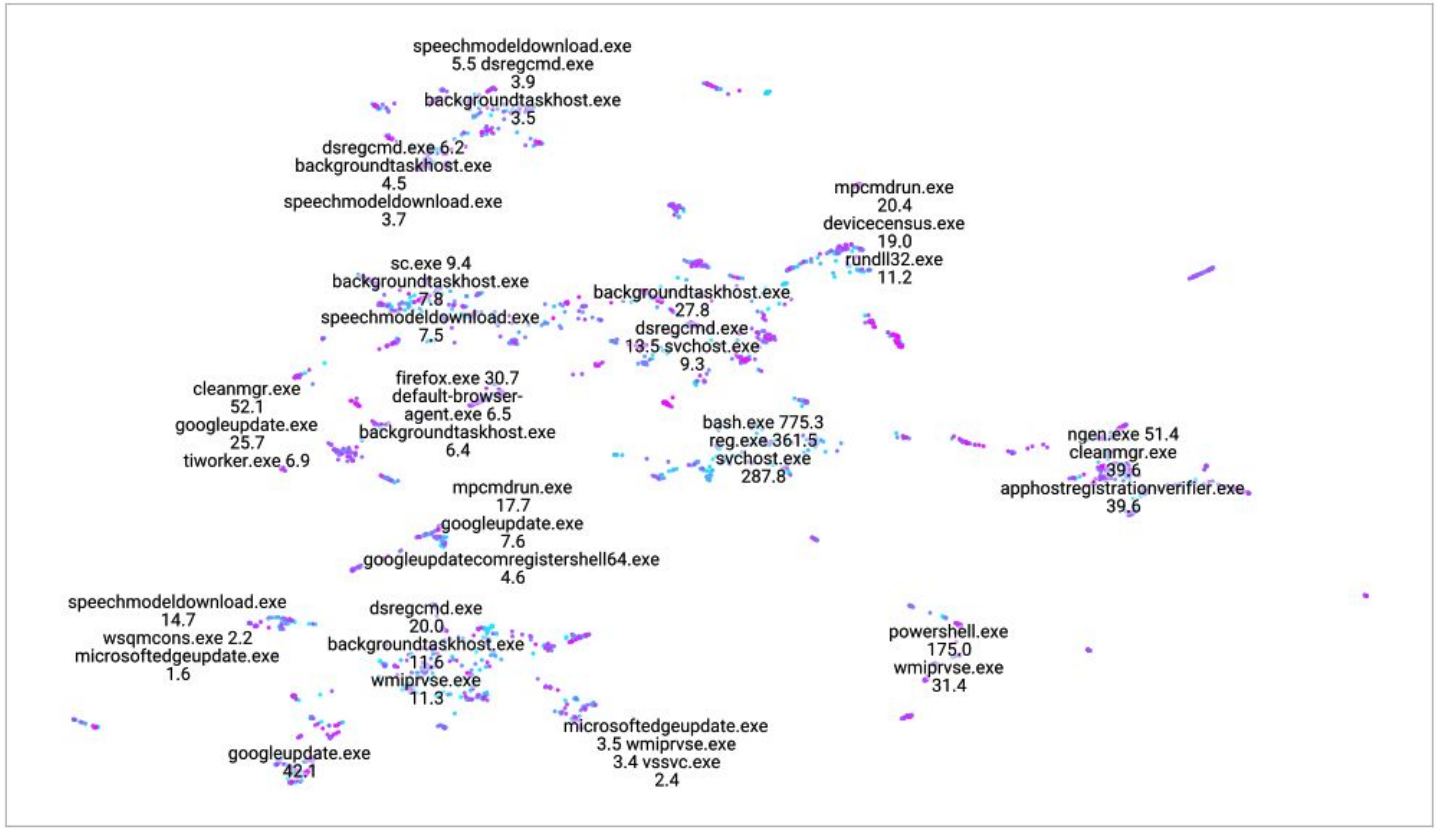
Process instances

as distributions over a cloud of code image cooccurrence vectors



Hosts over time

as distributions over a cloud of command line vectors



2023-11-05

2023-11-20

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Summary

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VECTORIZERS

UNIFORM MANIFOLD UMAP APPROXIMATION & PROJECTION

TNT THIS NOT THAT and DATAMAPPLOT

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```python
import vectorizers as vz, vectorizers.transformers as vzt, umap, fast_hdbscan, datamapplot

token_seqs = # Tokenize your data, yielding a list of lists of tokens.
vz_cooc = vz.TokenCooccurrenceVectorizer().fit(token_seqs)
vecs_cooc = vz_cooc.reduce_dimension(DIM_COOC)  # Unsure? Use 128 🤷

token_counts = vz.NgramVectorizer().fit_transform(token_seqs)
distribs_iwt = vzt.InformationWeightTransformer().fit_transform(tokens_counts)
vecs = vz.WassersteinVectorizer().fit_transform(distribs_iwt, vectors=vecs_cooc)

datamap = umap.UMAP(metric="cosine").fit_transform(vecs)
labels = # Find clusters in data map and figure names for them.
datamapplot.create_interactive_plot(datamap, labels, ...)
```

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The Tutte Institute for Mathematics and Computing (TIMC) is a government research institute focused on fundamental mathematics and computer science. Research work from the Institute that has been released as open source can be found here.

Software from the Tutte Institute and its staff

Vectorizers	UMAP	HDBSCAN	PyNNDescent	ThisNotThat
Tools for vectorizing sequence data	Dimension reduction and visualization	Spatial clustering	Approximate nearest neighbour search	Interactive data map exploration and labeling

Ensemble Clustering for Graphs	Graph Partition Measures	EnsTop	EasyData
Graph clustering and community detection	Graph partition evaluation	Ensemble topic modeling	Data science reproducibility framework

Glasbey	Fast HDBSCAN	DataMapPlot
Glasbey Algorithmic Categorical Colour Palettes	Fast Multicore HDBSCAN in Numba	Presentation Ready Data Map Plots

https://github.com/TutteInstitute

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https://github.com/TutteInstitute/acme3-mapping