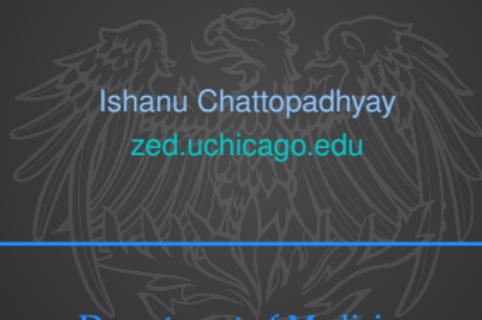


Granger Nets for Spatio-temporal Stochastic Inference: Predicting Earthquakes, Weather & Crime



Ishanu Chattopadhyay
zed.uchicago.edu

Department of Medicine
Institute For Genomics & Systems Biology

University of Chicago



Learning Patterns from Seismic Catalogs

1973-04-30T23:32:36.000Z,51.595,177.786,61,4.8,"Rat Islands, Aleutian Islands, Alaska"
1973-04-30T22:37:47.900Z,36.227,141.417,51,4.8,"near the east coast of Honshu, Japan"
1973-04-30T21:00:41.000Z,4.993,-77.96,23,5,"near the west coast of Colombia"
1973-04-30T16:39:49.800Z,29.93,131.612,62,4.4,"southeast of the Ryukyu Islands, Japan"
1973-04-30T15:55:21.100Z,-17.85,167.649,22,4.4,"Vanuatu"
1973-04-30T15:48:24.800Z,43.343,43.766,46,4.2,"Caucasus region, Russia"
1973-04-30T12:41:15.900Z,-10.867,166.812,33,4.2,"Santa Cruz Islands"
1973-04-30T11:55:29.200Z,60.951,-151.131,33,3.4,"Kenai Peninsula, Alaska"
1973-04-30T08:39:07.700Z,-17.514,179.623,613,5.4,"Fiji"
1973-04-30T07:29:48.700Z,50.993,89.734,33,4.6,"southwestern Siberia, Russia"

Time, location,
magnitude of events

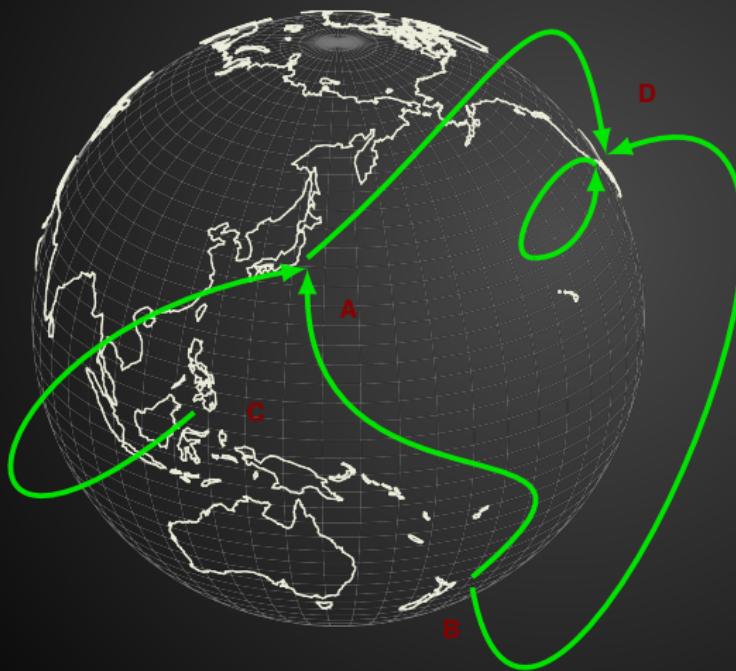


- Marian Anghel, LANL
- Yehuda Ben Zion, Geophysics, USC
- Hod Lipson, Data Science Institute, Columbia University



Towards Seismic Prediction

We Need To Model Cross-dependencies

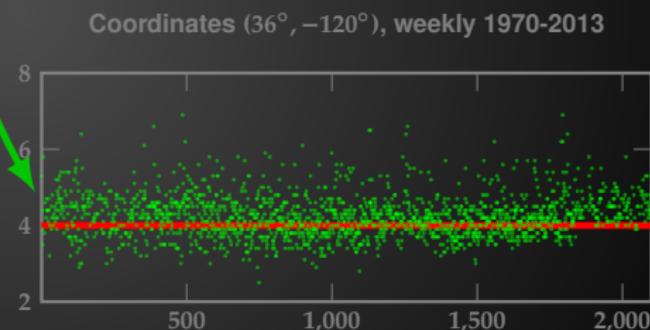


Do Faults Interact
Over Vast Distances
& Over Extended Time-periods?



Predicting Seismic Events

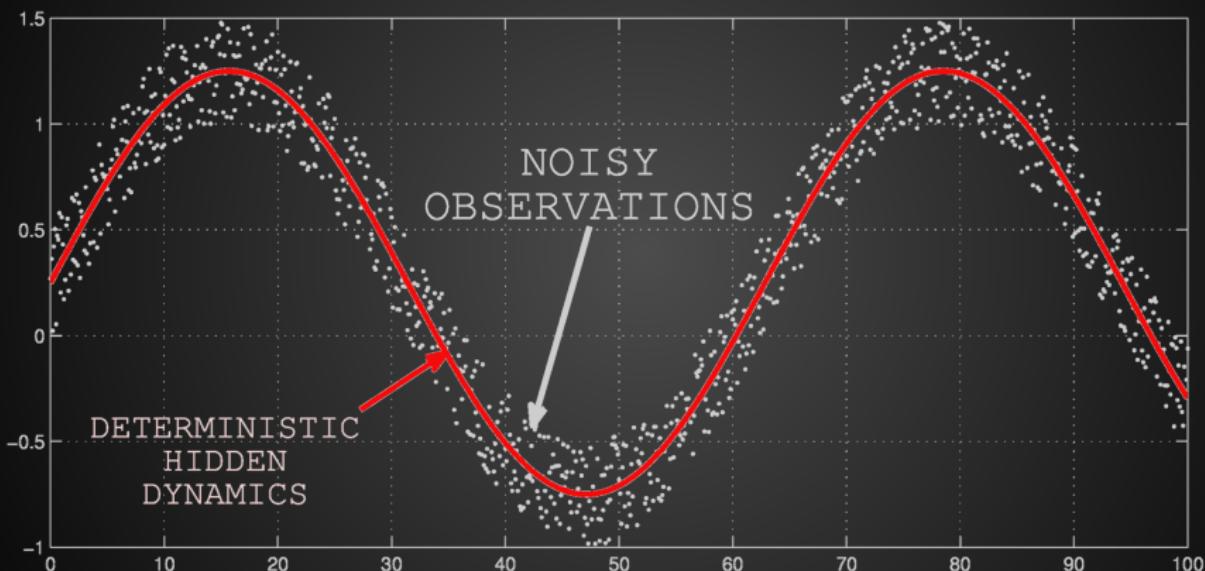
- Complex spatio-temporal stochastic processes drive seismic events
- Difficult to impossible to know parametric values for detailed simulations
- Can we simply mine the catalogs?





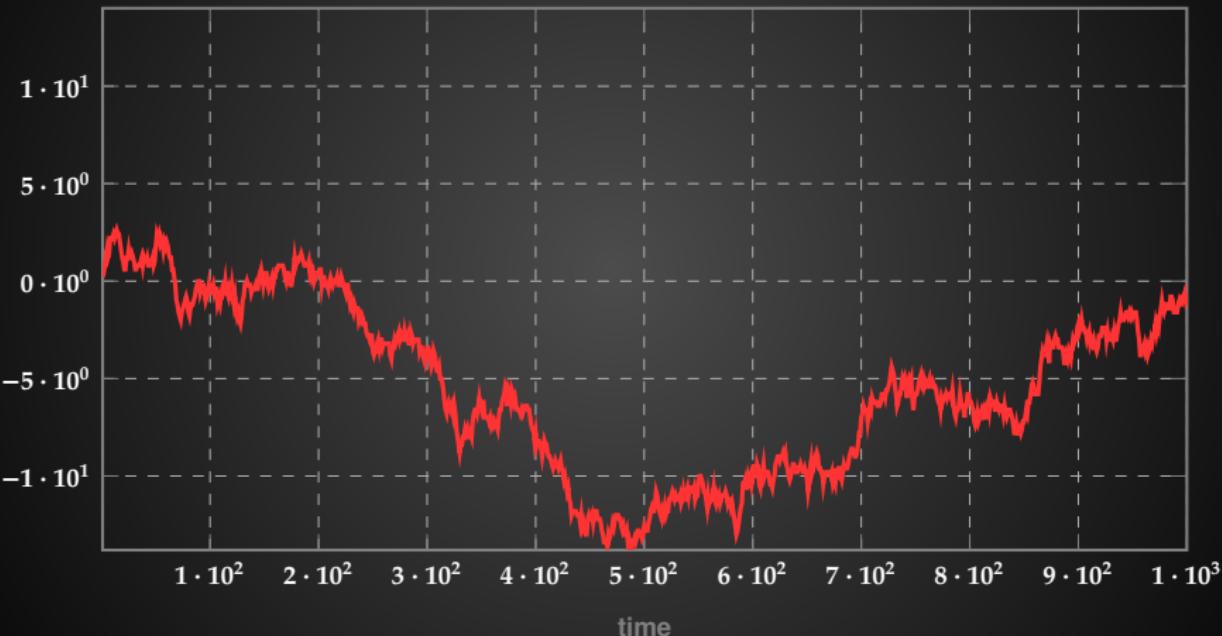


Stochastic Process \neq Deterministic + Noise



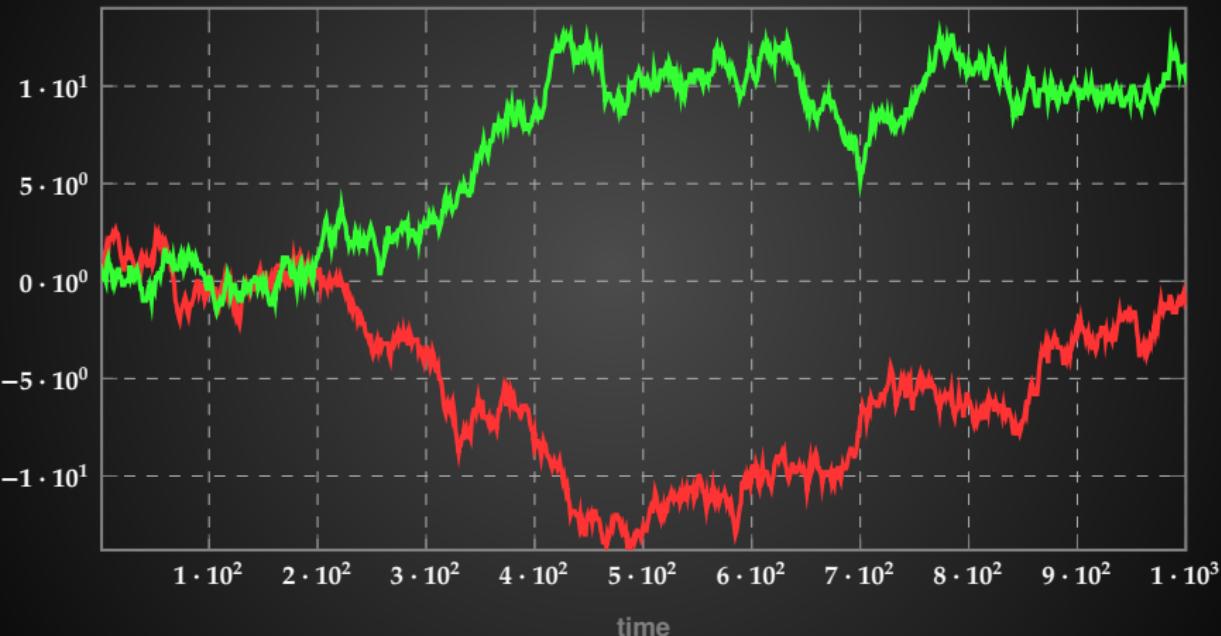


Stochastic Process \neq Deterministic + Noise





Stochastic Process \neq Deterministic + Noise





Exact Model
for unbiased coin

$$T \ (p=\frac{1}{2})$$

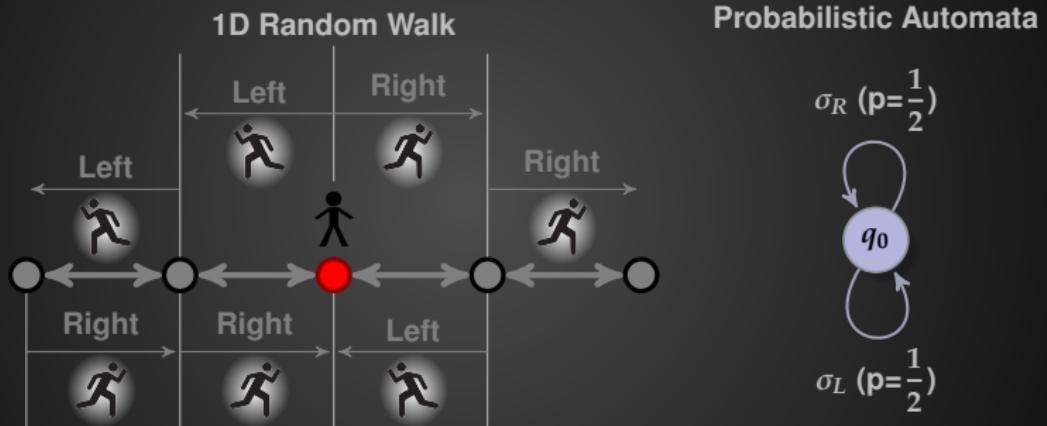


$$H \ (p=\frac{1}{2})$$



Can We Learn Models “Non-parametrically”

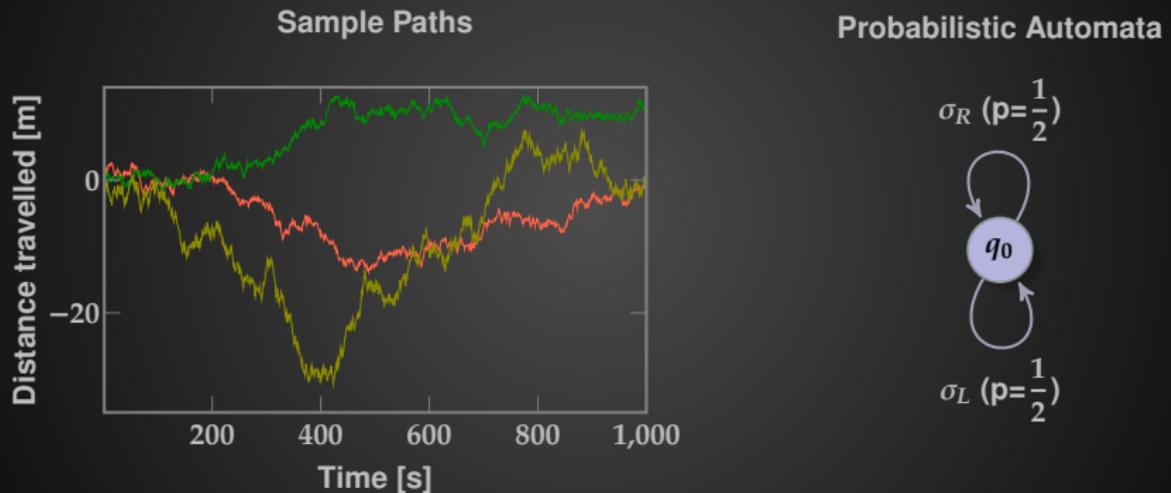
Probabilistic Automata As Stochastic Process Representations





Can We Learn Models “Non-parametrically”

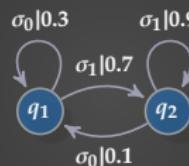
Probabilistic Automata As Stochastic Process Representations





Modeling Stochastic Processes

Probabilistic Automata

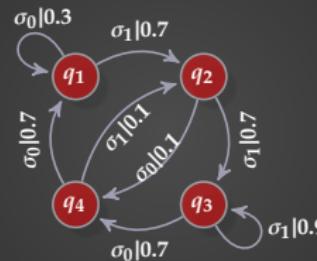


Last symbol determines the distribution of the next symbol



Modeling Stochastic Processes

Probabilistic Automata



Last 2 symbols determine the distribution of the next symbol



Probabilistic Finite State Automata

Models For Quantized Stationary Ergodic Stochastic Processes



State Set	Q	q_1, \dots, q_4
Alphabet	Σ	σ_0, σ_1
Morph probabilities	$\tilde{\pi} : Q \times \Sigma^* \rightarrow [0, 1]$	$\begin{pmatrix} 0.4 & 0.6 \\ 0.3 & 0.7 \\ 0.1 & 0.9 \\ 0.7 & 0.3 \end{pmatrix}$
Stationary distribution	φ^*	$\varphi^* P = \varphi^*$



Symbolic Derivatives

Estimating Average Immediate Future

λ	0.750285	0.249715
0	0.700112	0.299888
1	0.901009	0.0989909
00	0.699844	0.300156
01	0.899111	0.100889
10	0.700711	0.299289
11	0.918285	0.0817152
000	0.699004	0.300996
001	0.898769	0.10123
010	0.701038	0.298962
011	0.917181	0.0828194
100	0.701763	0.298237
101	0.899911	0.100089
110	0.697797	0.302203
111	0.930693	0.0693069
0000	0.699284	0.300716
0001	0.902025	0.0979754
:	:	:





Symbolic Derivatives

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1	0.901009	0.0989909
00	0.699844	0.300156
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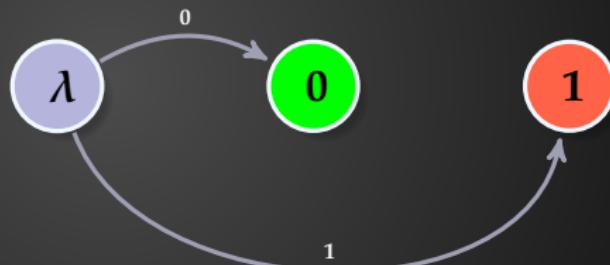




Symbolic Derivatives

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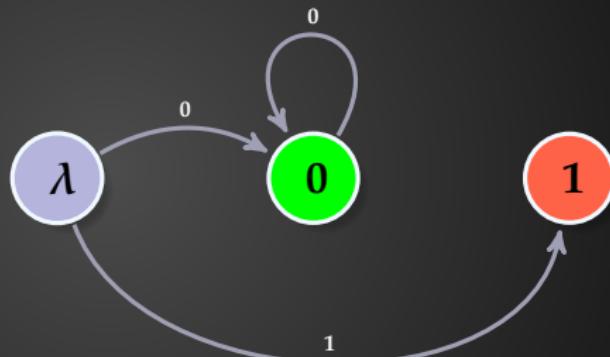




Symbolic Derivatives

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:	:	:

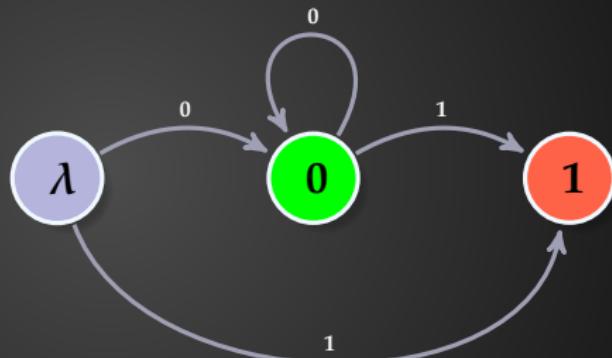




Symbolic Derivatives

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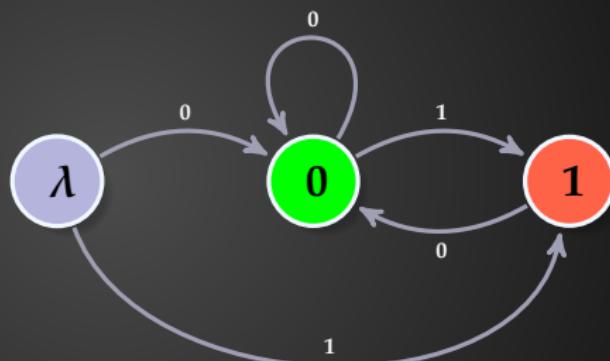




Symbolic Derivatives

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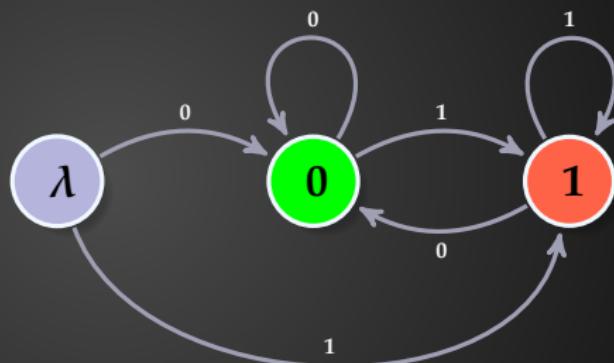




Symbolic Derivatives

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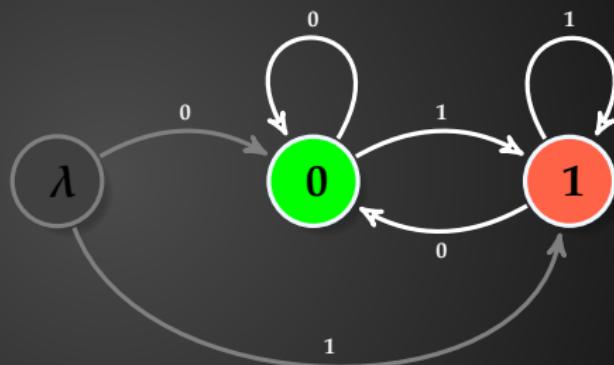




Symbolic Derivatives

Estimating Average Immediate Future

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:	:	:

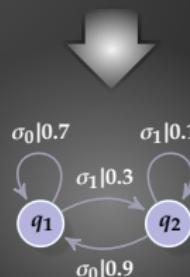
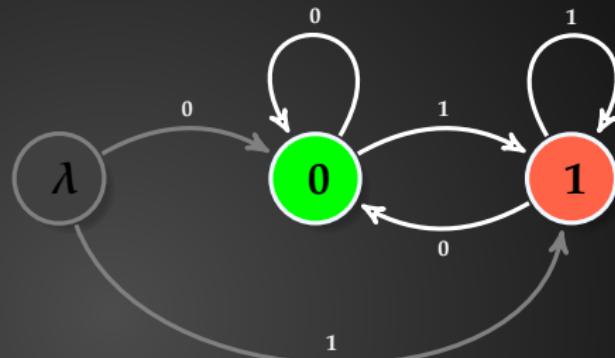




Symbolic Derivatives

Estimating Average Immediate Future

λ	0.750285	0.249715
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1	0.901009	0.0989909
00	0.699844	0.300156
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0000	0.699284	0.300716
0001	0.902025	0.0979754
:	:	:

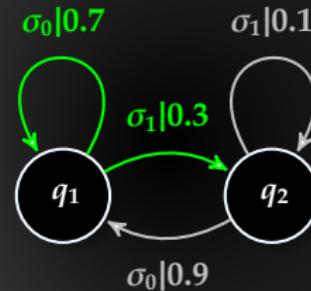




Symbolic Derivatives

Estimating Average Immediate Future

λ	0.750285	0.249715
0	0.700112	0.299888
1	0.901009	0.0989909
00	0.699844	0.300156
01	0.899111	0.100889
10	0.700711	0.299289
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001	0.898769	0.10123
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101	0.899911	0.100089
110	0.697797	0.302203
111	0.930693	0.0693069
0000	0.699284	0.300716
0001	0.902025	0.0979754
:	:	:
:	:	:



Merging of Symbolic Derivatives
Under ϵ Resolution

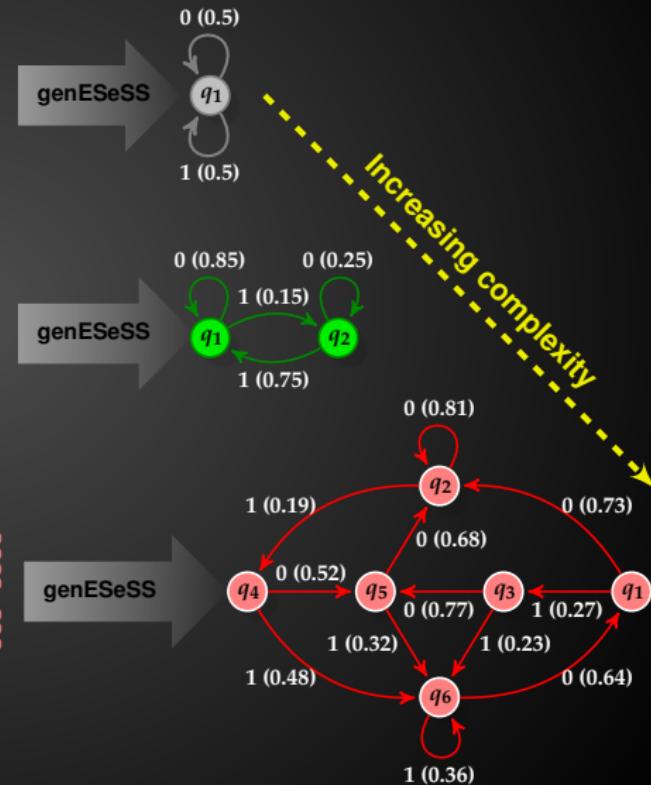


Learning Quantized Stochastic Processes

Algorithm GenESeSS

```
011011110011100110001100011101001111100101010011011000100100010011100010011  
110111010001000110100111001000110001111011001010100110110110110110110110111  
10000000011101110110001000111011100010001110001000111000100011100010001110000000000  
01111111111100000000000000000000000000000000000000000000000000000000000000000000000000  
11001111110000110100111100011100010111010001111110110101000111111000100100011111000  
11100111010001101001111000101110100011111100110111111001101101010100100100011111000  
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01010000110100100001010011101010110000001100001111101101010101100111101010001010101
```

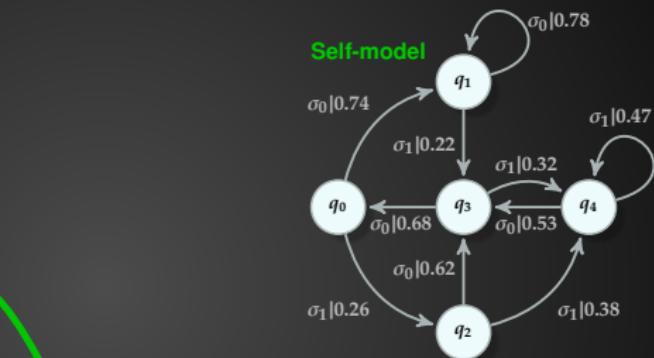
Flat White Noise (Fair Coin Toss Sequence)



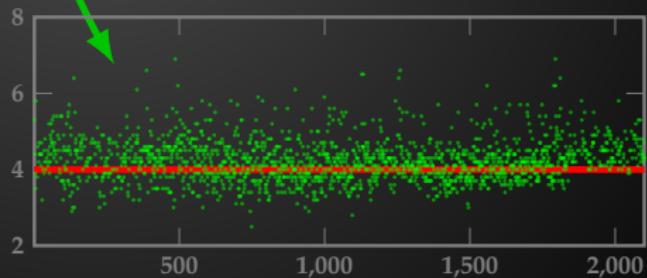


Predicting Seismic Events

With Both Space & Time Quantization

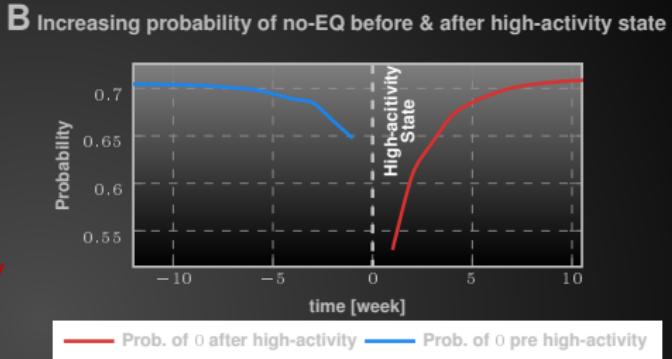
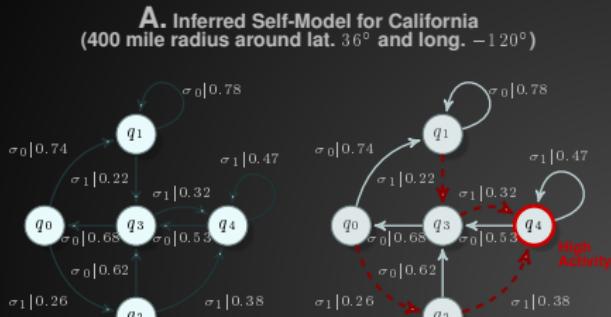


Coordinates $(36^\circ, -120^\circ)$, weekly 1970-2013

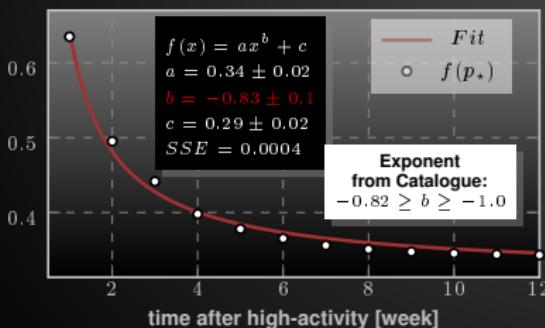




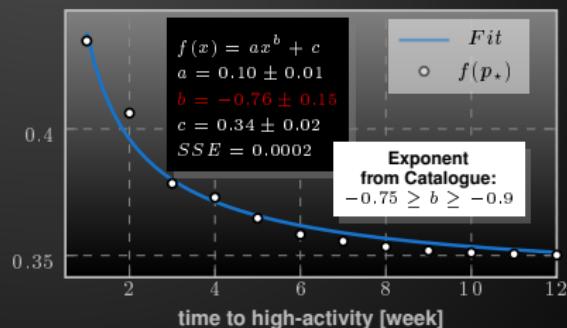
Validating The Omori-Utsu Law



D. Indirect Validation of Omori-Utsu Law (aftershocks)

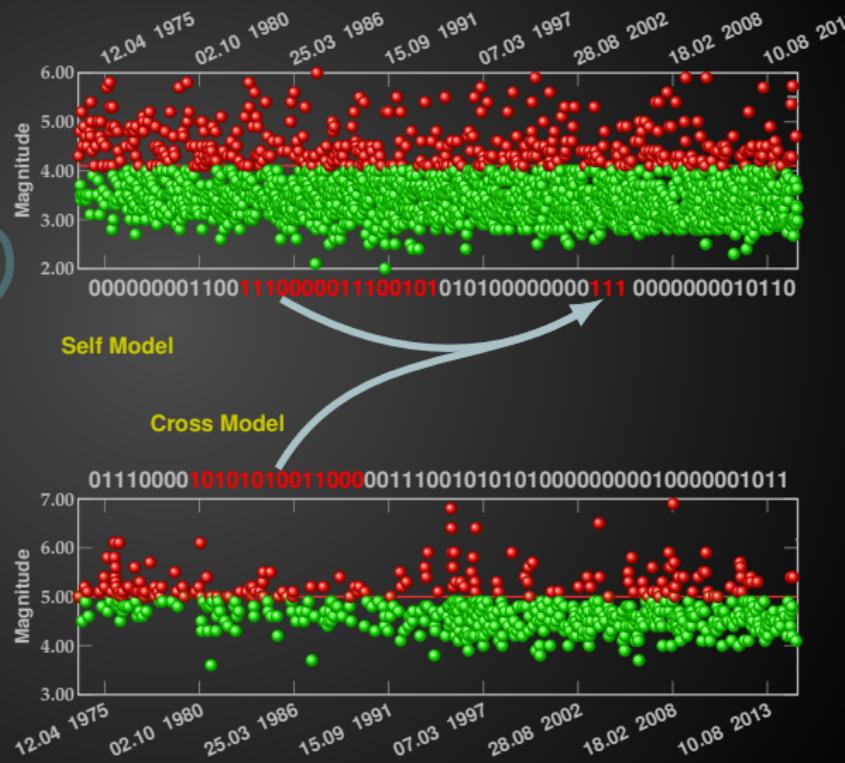
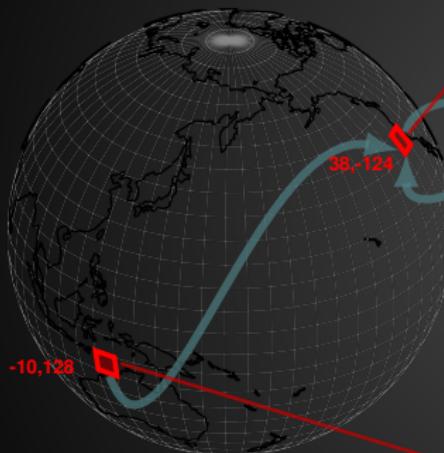


D. Indirect Validation of Omori-Utsu Law (foreshocks)





Seismic Spatio-temporal Inference Network (Spinets)

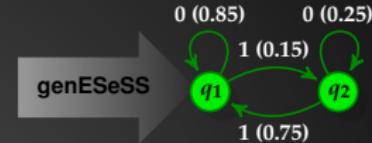




Inferring Cross-dependence

Probabilistic Transducers

```
0110000000001100001001101000110000000011000000110110000000000000000000000000000000  
01100000101101000100000000110110001001000010100000110000110000000000000000000000000  
00000000000000100100000000110000000011000011000000001100011101000000000000000001010000  
00110010010000011110000110011000011101000001110100000011001100100101110000000000110110  
00000011101100000000111010000011000101000000000000000000000000000000000000000000000000  
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  
00001010000110011000000110010000000110100000000000000000000000000000000000000000000000000000
```



A. Stochastic process on two letter alphabet

```
aaabbabbacababababcacacacccaaaabbbbaccacabbbbabbbbcaccacacccabbacc  
cabbbaccacabbacacbbaccacacabbababccacababcacaccabbababacaccabbacac  
abcbcfcbccaccacabcbcabababbacababababcacacacccaaaabbbbaccacabbb  
ababbbaccacacccabbaccabcccabbacacbbaccacacabbababccacabacac  
caabbacaccabbacacabcbcbccaccacabcabababcacacacccaaaabbbbaccac  
cababacacccaabbababacaccabbacacabcbcbccaccacabcbcabababbacabab
```

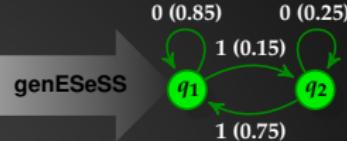
B. Stochastic process on 3 letter alphabet



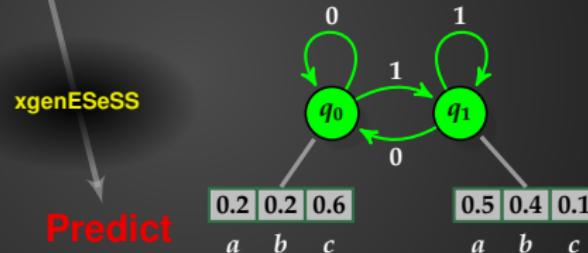
Inferring Cross-dependence

Probabilistic Transducers

```
0110000000011000010011010001100000001100  
01100001011010000000101100010010000  
000000000000100100000000010100000110000  
001100100100000011110000110011000000111  
0000000000110010000000011000000000010000  
00000000000000001100000000000000000000000  
00000000000000000000000000000000000000000  
00000000000000000000000000000000000000000  
00000000000000000000000000000000000000000  
00000000000000000000000000000000000000000  
00000000000000000000000000000000000000000  
000101000011001100000011001010000000011000
```



A. Stochastic process on two letter alphabet



aaababbacababababcacacaccccaaabb ? bbababbbcacccacccabbbbaccacabb
cabbbaccccabbacacbbaccaacacabbababccacabacbabacacacccaaaabbbaaccacabbb
abcacbcbbccaccacabcacbababacbabacacacccaaaabbbaaccacabbb
ababbbacccacaccabbacccabbbacccacbabacacbabccacabacbabac
caabbacacccabbacacbabacacbabacacbabacacacccaaaabbbaaccaca
cababacacaccaabbababacaccabbacacbabcbcbccaccacabcbcababababbacabab

B. Stochastic process on 3 letter alphabet



Coefficient Of Causality

Given two ergodic stationary quantized stochastic processes $\mathcal{H}_A, \mathcal{H}_B$ the coefficient of causal dependence of $\mathcal{H}_B \rightarrow \mathcal{H}_A$ is defined as:

$$\gamma_B^A = \frac{\text{expected change in entropy of the next symbol distribution in } \mathcal{H}_B \\ \text{due to observations in } \mathcal{H}_A}{\text{entropy of the next symbol distribution} \\ \text{in } \mathcal{H}_B \text{ in the absence of observations in } \mathcal{H}_A}$$

Using symbolic cross derivatives:

$$\gamma_B^A = 1 - \frac{E_{x \in \Sigma_A^*} \left(h \left(\phi_x^{\mathcal{H}_A, \mathcal{H}_B} \right) \right)}{h \left(\phi_\lambda^{\mathcal{H}_A, \mathcal{H}_B} \right)}$$

where $h(\cdot)$ is the discrete Shannon entropy.



Lots of Models Generated

Self-models: PFSAs, Cross-models: XPFSA

	σ_0	σ_1
q_0	0.8	0.2
q_1	0.8	0.2
q_2	0.8	0.2
q_3	0.8	0.2
q_4	0.6	0.4
q_5	0.8	0.2
q_6	0.7	0.3
q_7	0.7	0.3
q_8	0.7	0.3
q_9	0.8	0.2
q_{10}	0.7	0.3
q_{11}	0.9	0.1
q_{12}	0.9	0.1

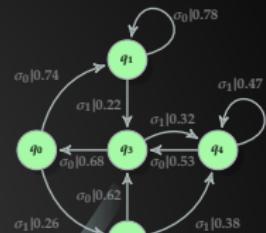


	σ_0	σ_1
q_0	0.1	0.9
q_1	0.1	0.9
q_2	0.2	0.8
q_3	0.2	0.8
q_4	0.2	0.8
q_5	0.1	0.9
q_6	0.2	0.8
q_7	0.1	0.9
q_8	0.3	0.7
q_9	0.2	0.8
q_{10}	0.1	0.9

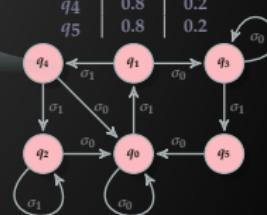


	σ_0	σ_1
q_0	0.1	0.9
q_1	0.2	0.8
q_2	0.1	0.9
q_3	0.2	0.8
q_4	0.1	0.9
q_5	0.2	0.8
q_6	0.1	0.9
q_7	0.2	0.8
q_8	0.1	0.9
q_9	0.2	0.8

	σ_0	σ_1
q_0	0.1	0.9
q_1	0.2	0.8
q_2	0.1	0.9
q_3	0.2	0.8
q_4	0.1	0.9
q_5	0.2	0.8
q_6	0.1	0.9
q_7	0.2	0.8
q_8	0.1	0.9
q_9	0.2	0.8



	σ_0	σ_1
q_0	0.7	0.3
q_1	0.7	0.3
q_2	0.8	0.2
q_3	0.8	0.2
q_4	0.8	0.2



	σ_0	σ_1
q_0	0.1	0.9
q_1	0.2	0.8
q_2	0.1	0.9
q_3	0.2	0.8
q_4	0.1	0.9

Models tested: 3,465,600

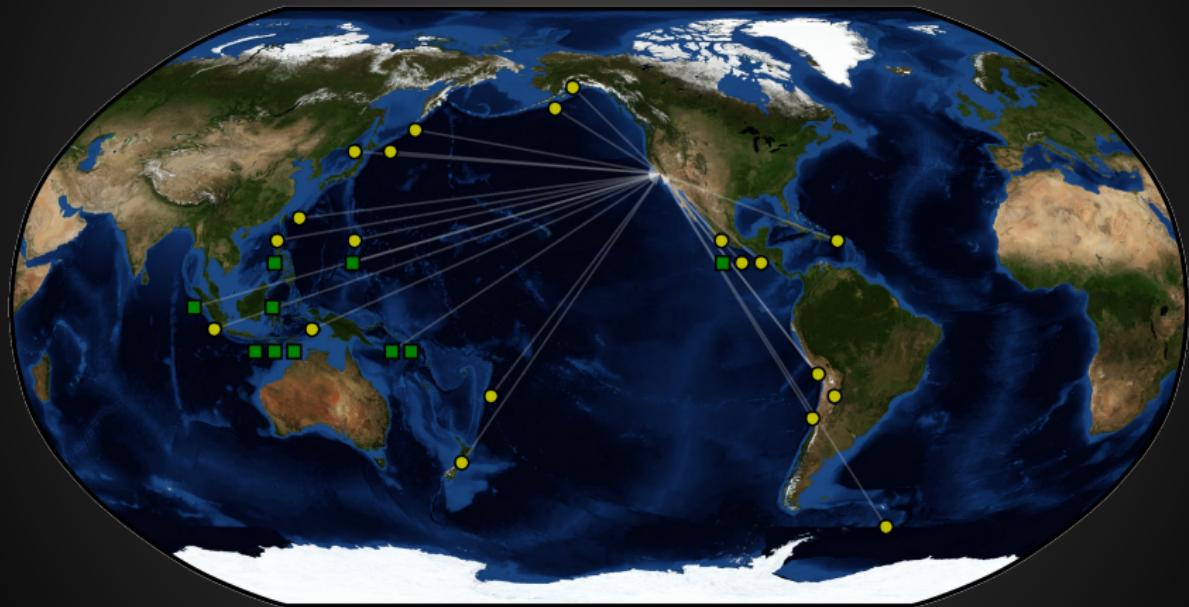
Compute time: \approx 30,000 core hours.

Models with $\gamma > 0.01$: 195, 884



Inferred Cross-Interactions For Earthquake Prediction California

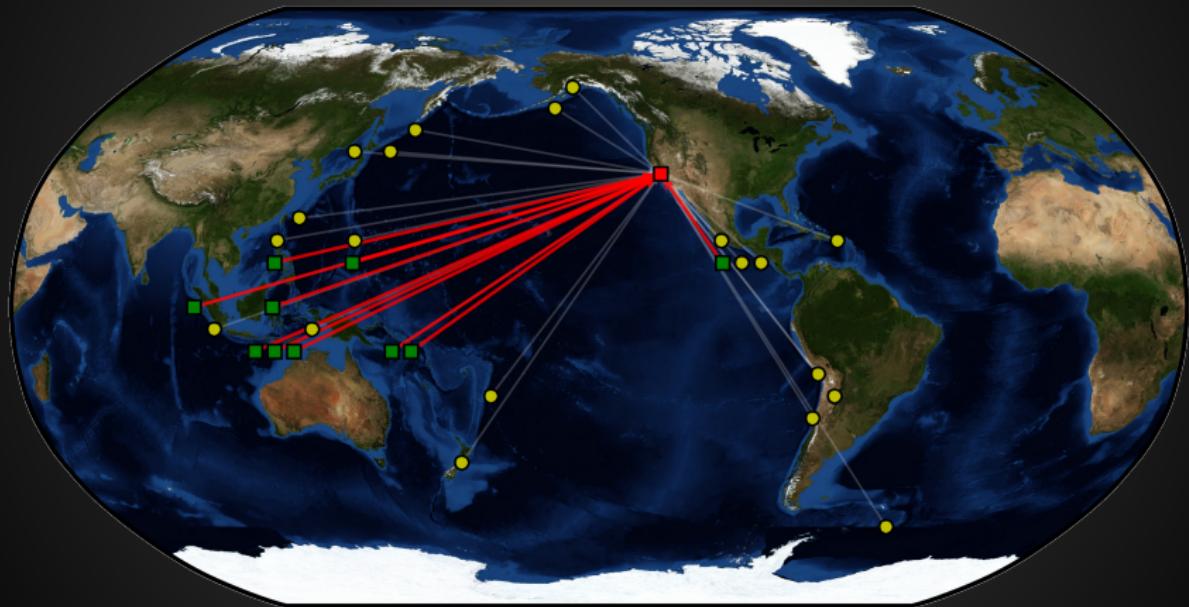
Infering The Pacific Ring of Fire

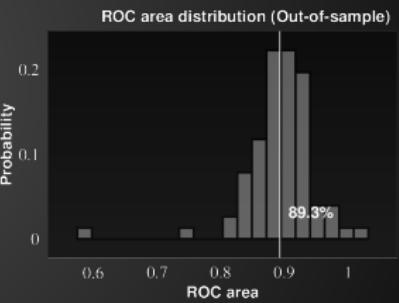
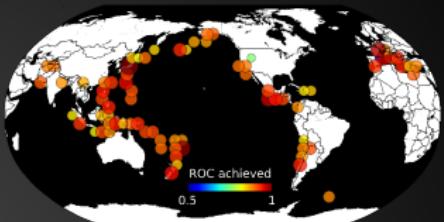
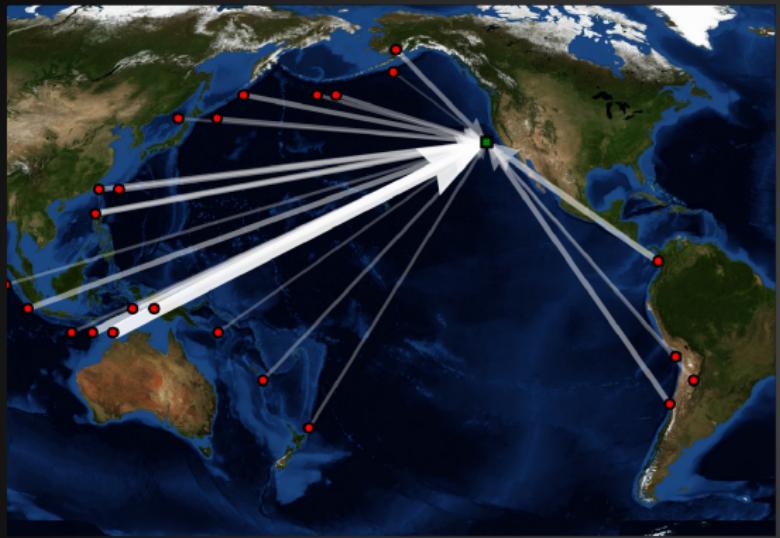




Inferred Cross-Interactions For Earthquake Prediction California

Infering The Pacific Ring of Fire







Prediction Performance: California Seismicity

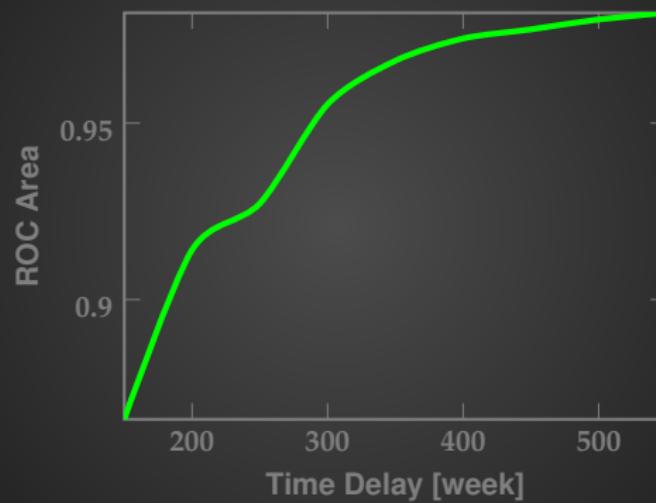
Prediction Horizon: 300 weeks





Prediction Performance Vs Time Delay

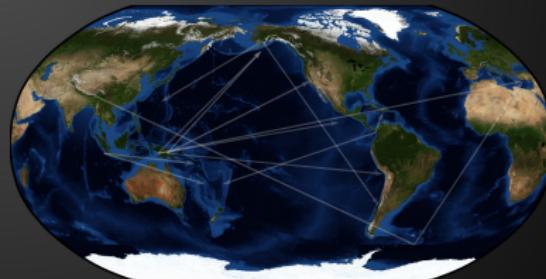
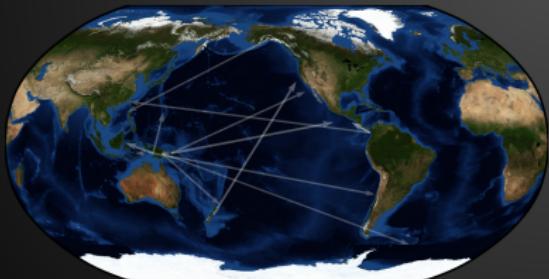
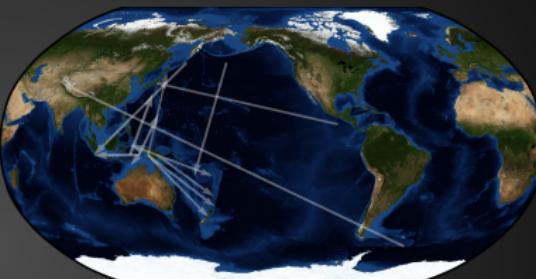
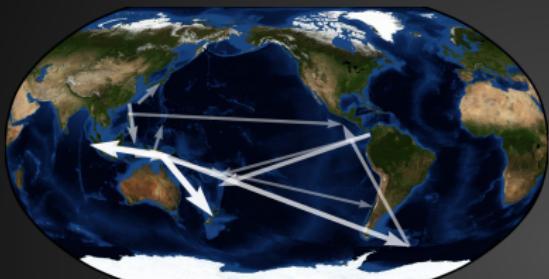
Postseismic Effects Last For A Decade





Inferred Global Network

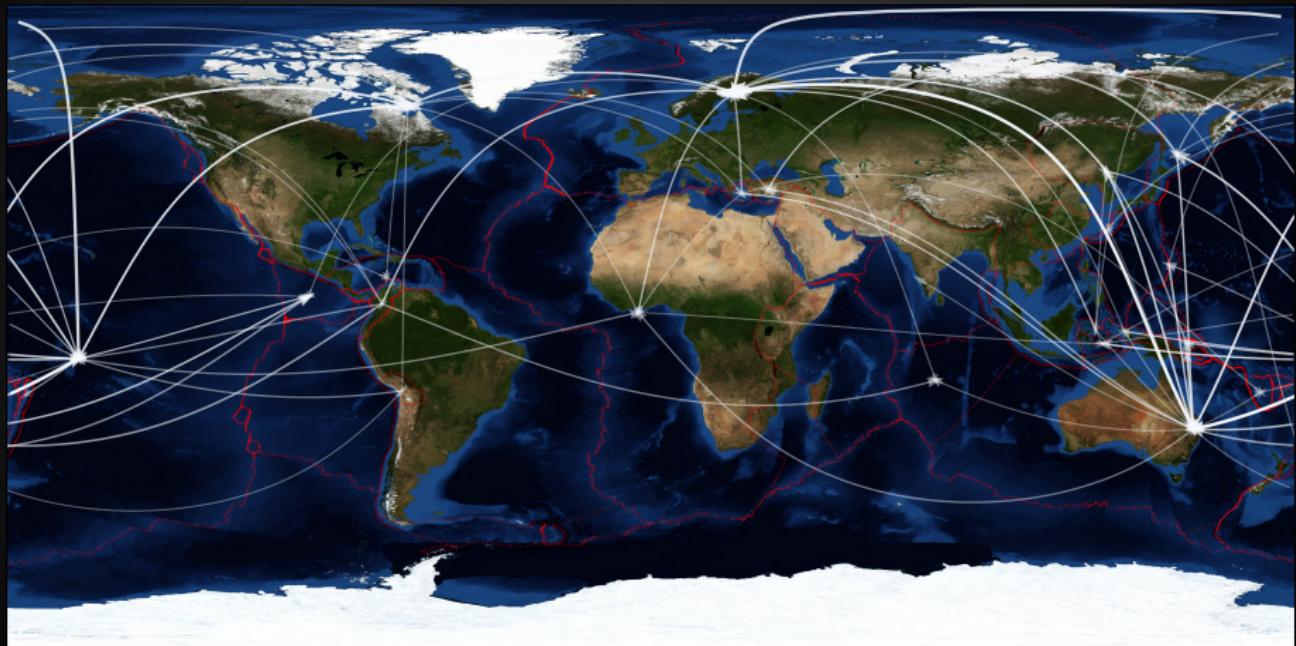
Top 20% of Inferred Connections





Inferred Global Network

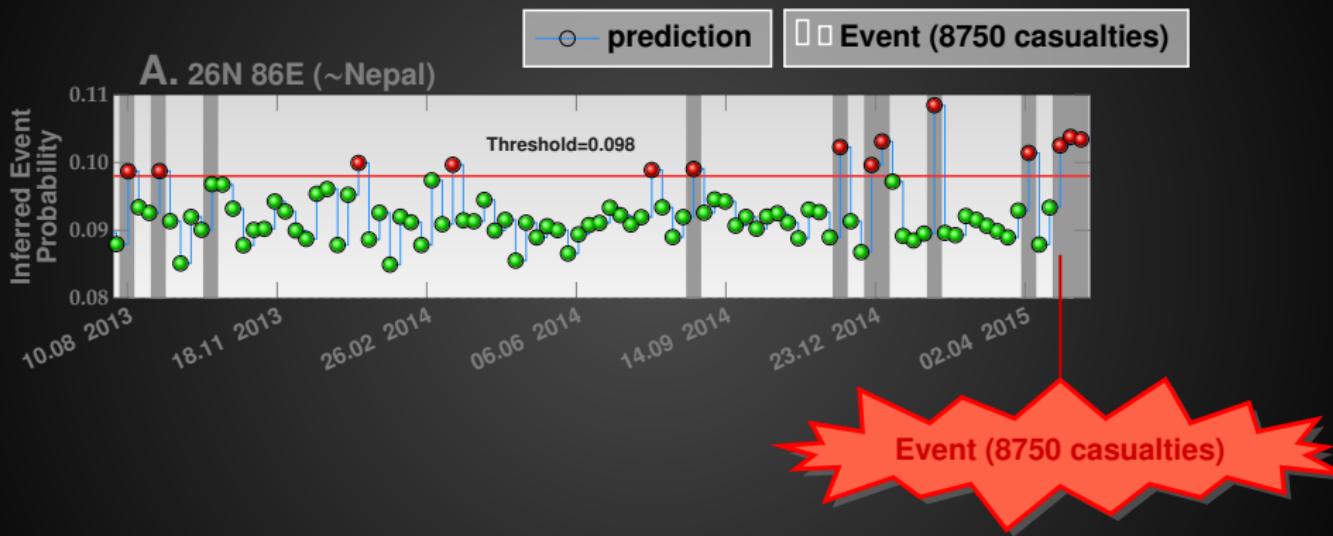
Normalized to Tectonic plates





Prediction Performance

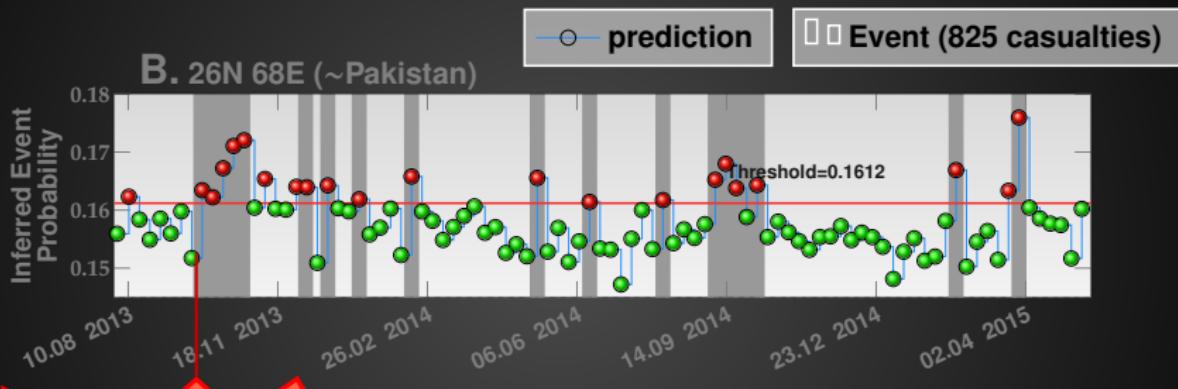
Out of Sample





Prediction Performance

Out of Sample

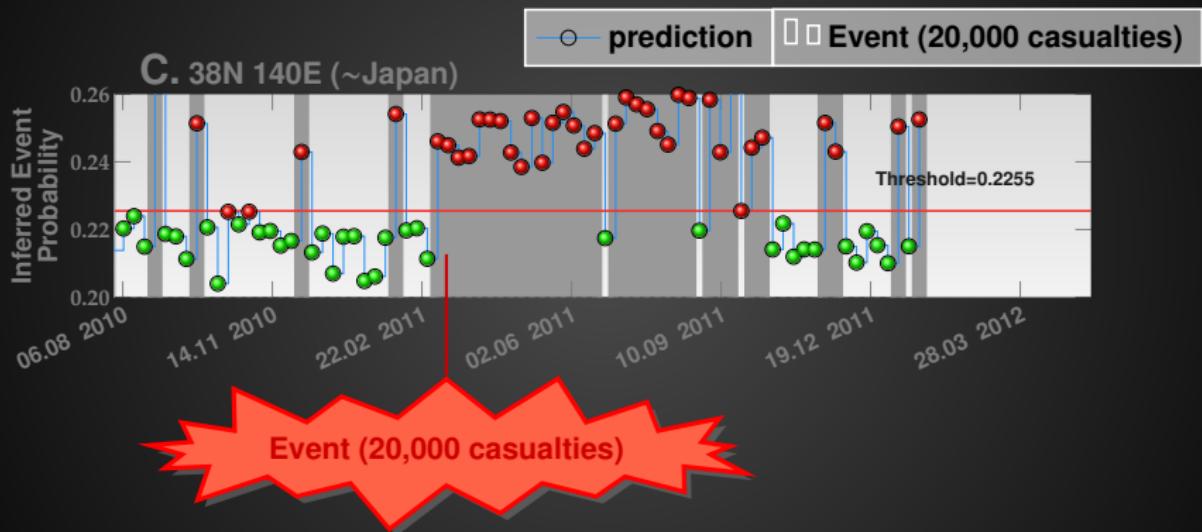


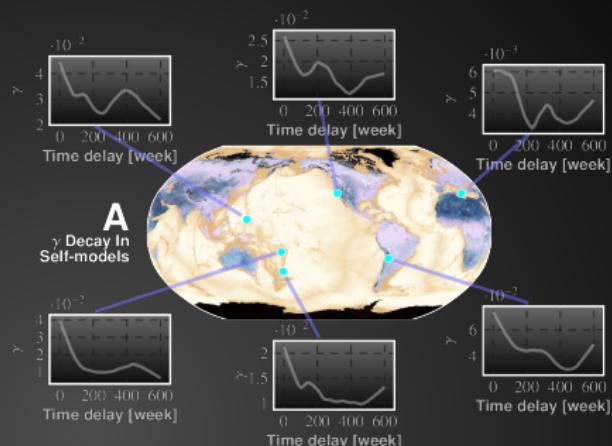
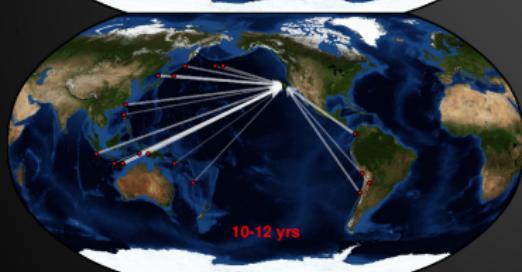
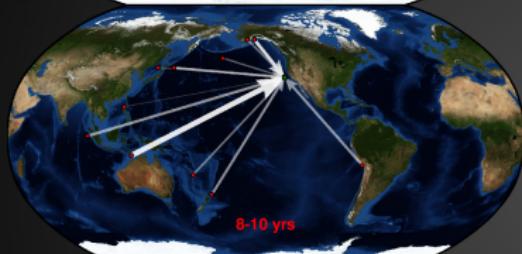
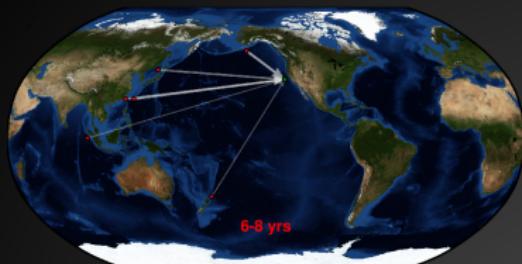
Event (825 casualties)



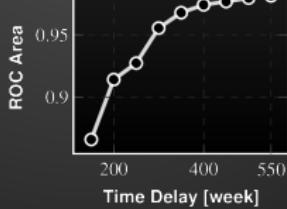
Prediction Performance

Out of Sample

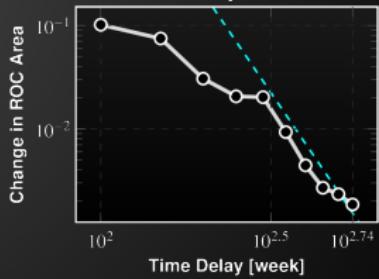




B ROC Area vs Time-delayed Models (Cumulative)



C ROC Area Increase From Time-delayed Models





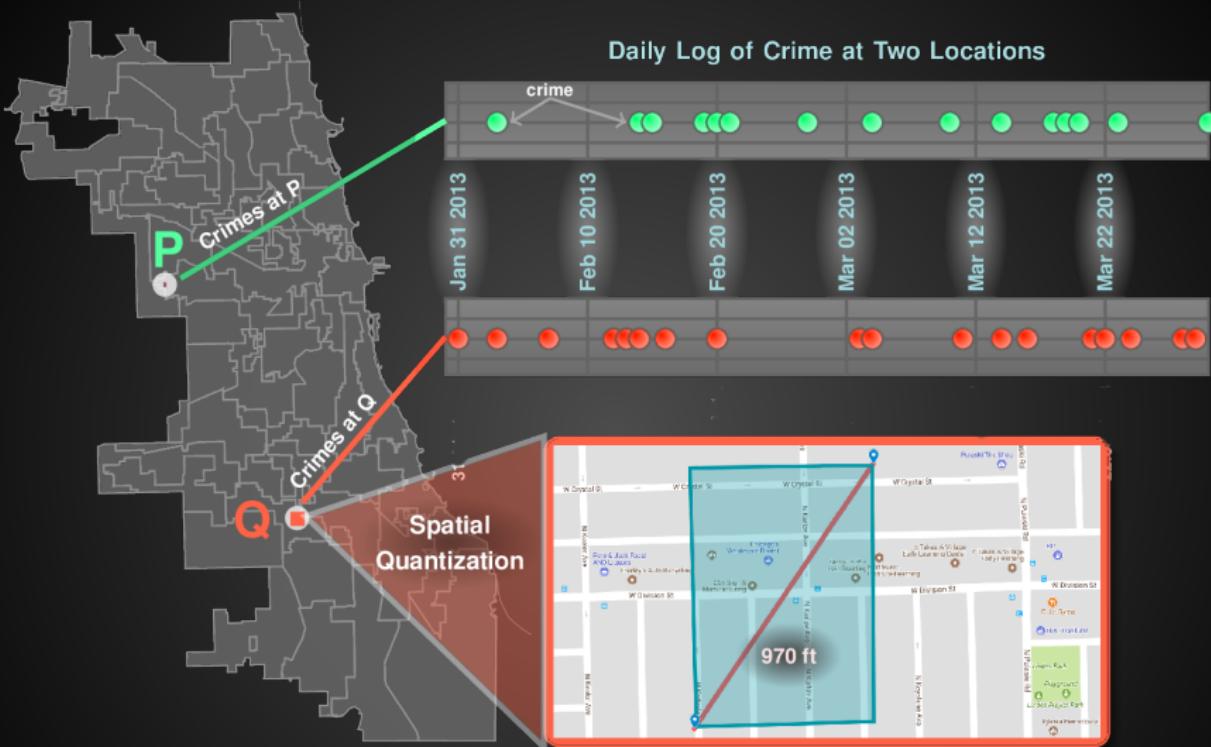
Crime Log: 2001-current

The City of Chicago

ID,Case Number,Date,Block,IUCR,Primary Type,Description,Location,Arrest,Domestic,Beat,District,Ward,Community Area,FBI Code,X Coordinate,Y Coordinate,Year,Updated On,Latitude,Longitude,Location

8316800,HT550945,08/11/2011 11:00:00 AM,086XX S MARQUETTE AVE,1120,DECEPTIVE PRACTICE,FORGERY,RESIDENCE,false,fals...
8316805,HT550781,10/20/2011 05:00:00 AM,056XX S ABERDEEN ST,0890,THEFT,FROM BUILDING,RESIDENCE,false,fals...
8316806,HT550706,10/20/2011 05:45:00 AM,079XX S LOOMIS BLVD,031A,ROBBERY,ARMED:HANDGUN,STREET,false,fals...
8316811,HT550932,10/12/2011 12:23:52 PM,003XX E 75TH ST,2027,NARCOTICS,POSS: CRACK,SMALL RETAIL STORE,true,fals...
8316814,HT551005,10/20/2011 10:40:00 AM,103XX S ELIZABETH ST,0484,BATTERY,PRO EMP HANDS NO/MIN INJURY,'SCHOOL, PUBLIC, BUILDING',true,fals...
8316821,HT551028,10/20/2011 10:50:00 AM,040XX W VAN BUREN ST,3731,INTERFERENCE WITH PUBLIC OFFICER,OBSTRUCTING IDENTIFICATION,STREET,true,fals...
8316822,HT551031,10/19/2011 02:00:00 AM,071XX W DICKENS AVE,0910,MOTOR VEHICLE THEFT,AUTOMOBILE,SIDEWALK,false,fals...
8316824,HT551032,10/20/2011 12:00:00 AM,034XX N NATECH AVE,2825,OTHER OFFENSE,HARASSMENT BY TELEPHONE,RESIDENCE,false,fals...
8316825,HT549690,10/19/2011 12:51:00 PM,079XX S ADA ST,2820,OTHER OFFENSE,TELEPHONE THREAT,APARTMENT,false,fals...
8316826,HT549865,10/19/2011 06:00:00 AM,011XX N LEAMINGTON AVE,0810,THEFT,OVER \$500,RESIDENTIAL YARD (FRONT/BACK),false,fals...
8316827,HT550935,09/01/2011 04:00:00 PM,079XX S LOOMIS BLVD,0610,BURGLARY,FORCIBLE ENTRY,RESIDENCE,GARAGE,false,fals...
8316838,HT548010,10/17/2011 03:20:00 PM,055XX N KEDZIE AVE,0802,THEFT,\$500 AND UNDER,'SCHOOL, PUBLIC, GROUNDS',true,fals...
8316839,HT551049,10/20/2011 08:50:00 AM,102XX S AVENUE N,0430,BATTERY,AGGRAVATED: OTHER DANG WEAPON,STREET,false,fals...
8316841,HT550977,10/19/2011 02:50:00 PM,029XX W POLK ST,0545,ASSAULT,PRO EMP HANDS NO/MIN INJURY,'SCHOOL, PUBLIC, BUILDING',false,fals...
8316842,HT548248,08/06/2011 06:00:00 AM,028XX N MONTCLARE AVE,0620,BURGLARY,UNLAWFUL ENTRY,RESIDENCE,GARAGE,false,fals...
8316843,HT551037,10/20/2011 11:00:00 AM,040XX W WILCOX ST,0486,BATTERY,DOMESTIC BATTERY SIMPLE,RESIDENCE PORCH/HALLWAY,true,fals...
8316845,HT550944,10/16/2011 05:00:00 AM,008XX N KEYSTONE AVE,0610,BURGLARY,FORCIBLE ENTRY,RESIDENCE,fals...
8316846,HT549243,10/18/2011 06:00:00 PM,001XX S STATE ST,0810,THEFT,OVER \$500,COMMERCIAL / BUSINESS OFFICE,fals...
8316849,HT537575,10/11/2011 11:05:00 AM,031XX W 40TH PL,1811,NARCOTICS,POSS: CANNABIS 30GMS OR LESS,ALLEY,true,fals...
8316851,HT549751,10/19/2011 01:35:00 PM,007XX N PALUSKI RD,0545,ASSAULT,PRO EMP HANDS NO/MIN INJURY,'SCHOOL, PUBLIC, BUILDING',false,fals...
8316857,HT549795,10/19/2011 01:40:00 PM,008XX N CICERO AVE,0860,THEFT,RETAIL,THEFT,CONVENIENCE STORE,fals...
8316858,HT550743,10/20/2011 07:15:00 AM,047XX W HURON ST,1310,CRIMINAL DAMAGE,TO PROPERTY,RESIDENTIAL YARD (FRONT/BACK),false,fals...
8316861,HT550987,10/20/2011 07:30:00 AM,053XX W BELLE PLAINE AVE,0917,MOTOR VEHICLE THEFT,CYCLE, SCOOTER, BIKE -W/N',STREET,true,fals...
8316863,HT546138,10/15/2011 03:30:00 PM,036XX N BROADWAY,0802,BURGLARY,UNLAWFUL ENTRY,CONSTRUCTION SITE,fals...
8316869,HT550991,10/20/2011 12:00:01 AM,007XX W BRIAR PL,0810,THEFT,OVER \$500,STREET,true,fals...
8316870,HT550911,10/20/2011 09:39:00 AM,061XX N BROADWAY,0860,THEFT,RETAIL THEFT,DRUG STORE,true,fals...
8316871,HT549680,10/19/2011 01:03:00 PM,044XX N BROADWAY,0460,BATTERY,SIMPLE,DEPARTMENT STORE,fals...
8316872,HT551071,10/19/2011 03:00:00 PM,053XX S CALUMET AVE,0810,THEFT,OVER \$500,RESIDENCE,fals...
8316873,HT551063,10/20/2011 11:10:00 AM,003XX E 47TH ST,1811,NARCOTICS,POSS: CANNABIS 30GMS OR LESS,SIDEWALK,true,f...
8316874,HT550901,10/20/2011 09:11:00 AM,033XX W OGDEN AVE,2022,NARCOTICS,POSS: COCAINE, POLICE FACILITY/VEH PARKING LOT,true,fals...
8316875,HT549739,10/19/2011 01:30:00 PM,002XX E GARFIELD BLVD,0820,THEFT,\$500 AND UNDER,CTA BUS,fals...
8316880,HT549802,10/19/2011 12:00:00 PM,011XX W WILSON AVE,0460,BATTERY,SIMPLE,COLLEGE,UNIVERSITY GROUNDS,fals...
8316881,HT431449,08/04/2011 11:00:00 AM,027XX W CHICAGO AVE,0820,THEFT,\$500 AND UNDER,STREET,fals...
8316882,HT549162,10/19/2011 06:42:00 AM,105XX S WESTERN AVE,0610,BURGLARY,FORCIBLE ENTRY,TAVERN/LIQUOR STORE,fals...
8316884,HT544972,10/12/2011 04:30:00 AM,103XX S HALSTED ST,1310,CRIMINAL DAMAGE TO PROPERTY,SMALL RETAIL STORE,fals...
8316886,HT549777,10/19/2011 02:10:00 PM,014XX W PRATT BLVD,0850,THEFT,ATTEMPT THEFT,SMALL RETAIL STORE,fals...
8316887,HT551046,10/20/2011 11:00:00 AM,050XX N WINTHROP AVE,2820,OTHER OFFENSE,TELEPHONE THREAT,RESIDENCE,fals...
8316889,HT550997,10/20/2011 09:10:00 AM,041XX N DICKINSON AVE,1121,DECEPTIVE PRACTICE,COUNTERFEITING DOCUMENT,STREET,true,fals...
8316890,HT532459,10/07/2011 11:46:00 AM,062XX S VERNON AVE,2092,NARCOTICS,SOLICIT NARCOTICS ON PUBLIC/WAY,SIDEWALK,true,fals...
8316892,HT551045,10/20/2011 04:55:00 AM,009XX N HAMILIN AVE,1822,NARCOTICS,MAN/DEL,CANNABIS OVER 10 GMs,RESIDENTIAL YARD (FRONT/BACK),true,fals...
8316893,HT551023,10/20/2011 02:00:00 AM,061XX S STEWART AVE,0810,THEFT,OVER \$500,STREET,fals...
8316894,HT550772,10/20/2011 07:10:00 AM,048XX N TALMAN AVE,1320,CRIMINAL DAMAGE,TO VEHICLE,STREET,fals...
8316895,HT551029,10/20/2011 09:30:00 AM,007XX W VAN BUREN ST,0920,MOTOR VEHICLE THEFT:TT,AUTOMOBILE,VEHICLE NON-COMMERCIAL,fals...
8316898,HT551055,10/16/2011 09:00:00 AM,018XX S LAFLIN ST,1365,CRIMINAL TRESPASS,TO RESIDENCE,APARTMENT,fals...

Daily Log of Crime at Two Locations

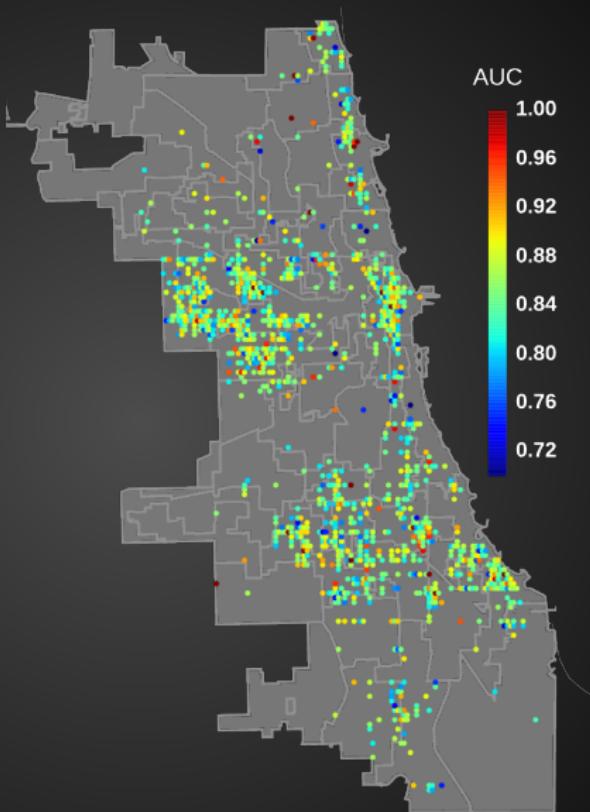


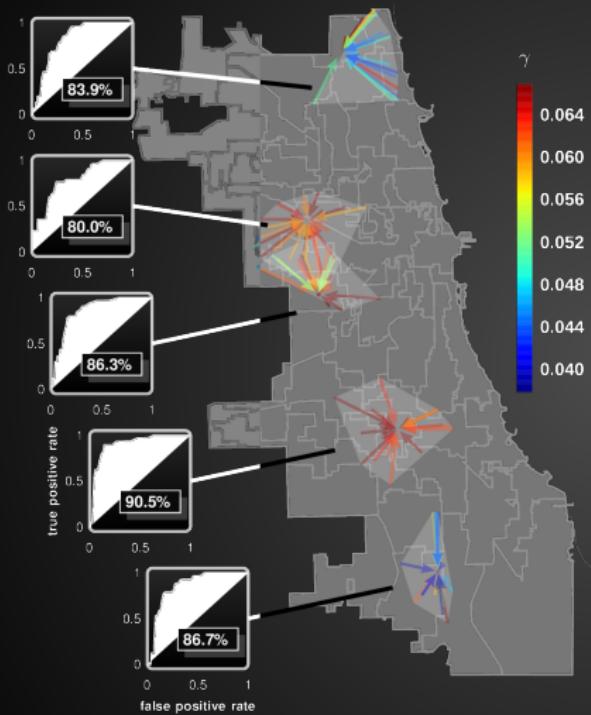
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Analysis Results



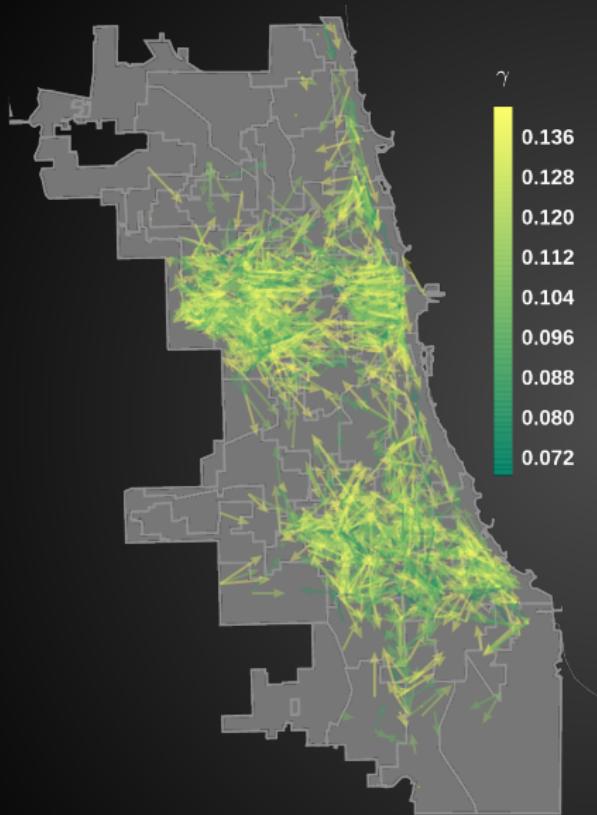
Spatial AUC achieved



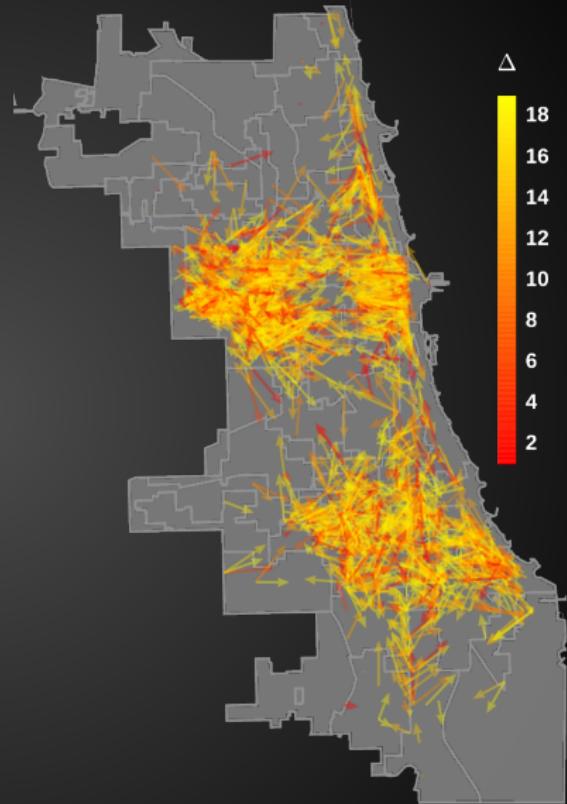


Tiles analyzed	1229
Mean AUC achieved	approx. 89.2%
Temporal memory	approx. 20 days
Spatial memory	approx. 3 miles
Out-of-sample period	approx. 100 days in 2016
Learning period	approx. 3 years
Event Resolution	Binary (Crime vs No-crime)

Spatial distribution of γ



Spatial Distribution of Δ





Conclusions

- Reverse-engineering spatio-temporal logs to distill predictive models
 - Online predictors under development
-

Acknowledgements:

- The Neubauer Collegium for Culture and Society
- DARPA D3M