A Data-Driven Early Warning System for Mining Accident

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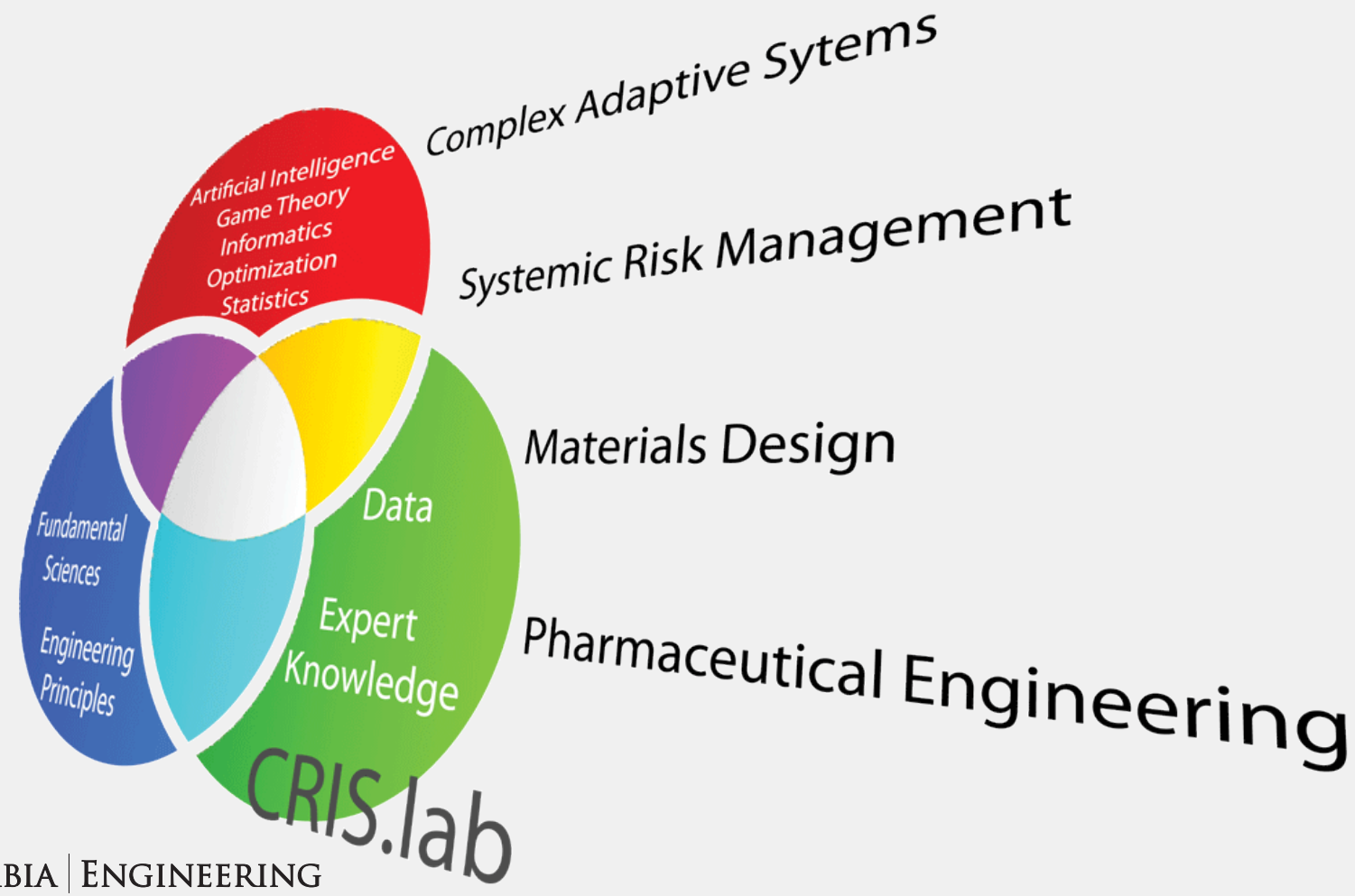
Complex, Resilient, Intelligent Systems (CRIS Lab)



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Systemic Risk

- Systemic disasters
  - SARS (2003)
  - Northeast Blackout (2003)
  - Subprime Crisis (2008)
  - Deepwater Horizon Oil Spill (2010)
- Emerging systemic risks
  - Climate change
  - Income/wealth inequality
  - Cyber-physical security
  - Technological singularity
- Fast-paced and connected
- Design complex systems
- Analyze systemic risk

Upper Big Branch Mine Disaster (2010)

- April 5, 2010, Raleigh County, West Virginia, owned by Massey Energy
- 29 deaths, the worst mining in the United States since 1970
- MSHA cites corporate culture as root cause of Upper Big Branch Mine disaster

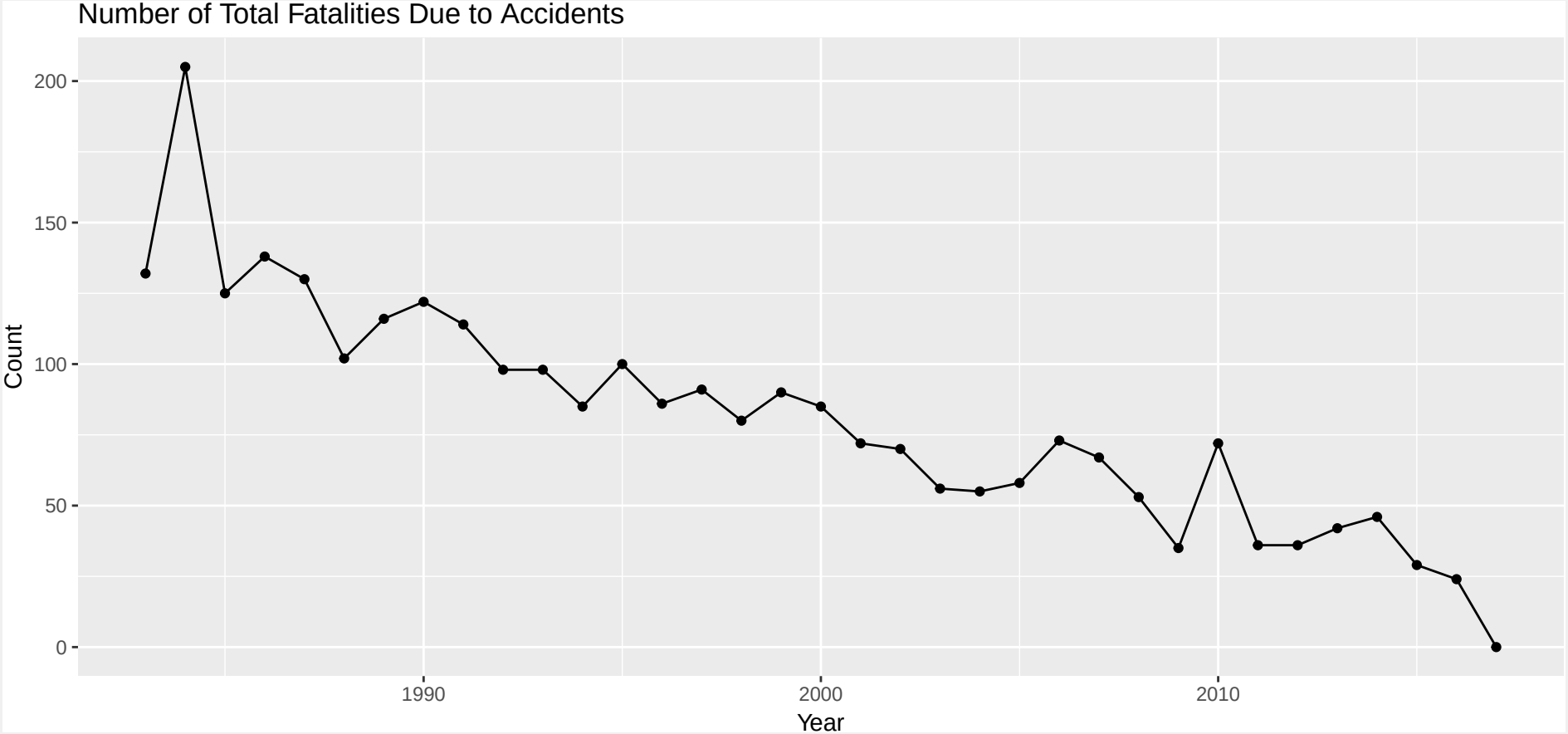
Sago Mine Disaster (2006)

- January 2, 2006, Sago, West Virginia, owned by Anker West Virginia Mining
- 13 miners were trapped for nearly two days; only one survived
- Fatality number was exceeded by the Upper Big Branch Mine disaster
- MSHA reports prior history of safety violations and fatalities

Mine Safety and Health Administration (MSHA)

- Formed in 1977
- Agency of the United States Department of Labor
- Mission
  - Prevent death, illness, and injury from mining
  - Promote safe and healthful workplaces for U.S. miners
  - Develop and enforce safety and health rules
  - Provide technical, educational, and other types of assistance
- A constantly improving industry in terms of safety

Fatality Trend Since 1983



Can We Further Improve Mine Safety?

- Process MSHA safety data
- Understand the underlying causal relationships
- Develop early warning systems based on past behaviors
- Credit rating/score analogy
  - Predict default probability within 18 months
  - Accidents: defaults a month or a year prior to application
  - Violations: missed payments, late payments, etc.
- Can we develop a "credit score" for mine safety?

Department of Labor Enforcement Data

- Link: https://enforcedata.dol.gov/views/data_catalogs.php
- Updated daily or weekly
- Publicly available
  - Department of Labor: MSHA, OSHA, etc.
  - Other departments: EPA, FDA, DOJ, etc.

MSHA Data: Sources

- Mine accidents table: "msha_accident.csv"
  - 681,386 rows
  - Retrieved 1/26/2017, from https://enforcedata.dol.gov/views/data_summary.php
- MSHA assessed violations table: "AssessedViolations.csv"
  - 2,169,804 rows
  - Retrieved 12/10/2016, from https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp

MSHA Data: Advantages

- Each mine has a unique mine ID, e.g., Upper Big Branch (4608436)
- Rich details: e.g., classification, description, and severity
- Selected attributes from the accidents table (omitting 42 attributes)

```
##  [1] "mine_id"          "controller_id"    "cal_yr"
##  [4] "cal_qtr"          "ai_dt"            "inj_degr_desc"
##  [7] "ai_class_desc"    "ai_occ_desc"      "ai_acty_desc"
## [10] "exper_tot_calc"   "exper_mine_calc"  "exper_job_calc"
## [13] "ai_narr"          "accident_type_cd" "no_injuries"
## [16] "days_restrict"    "days_lost"
```

MSHA Data: Challenges

- Missing data, human errors
- No information about inactive/nonoperating mines
- Most data are not numeric
- Lots of zeros, few severe accidents ($\sim 0.5\%$)

Consolidated Data

- Group and summarize accidents/violations by mines
- 664,128 rows, 10,377 unique mines
- From 2000 to 2015
- Each row represents data for a unique combination of mine, year, and quarter
  - e.g., Upper Big Branch Mine in the second quarter of 2010
- Each row contains both current and past information
  - i.e., current quarter, past quarter, past year, and past three years

Consolidated Data

- All 25 attributes of the consolidated data

```
##  [1] "mine_id"                    "mine.name"
##  [3] "year"                       "quarter"
##  [5] "active"                     "num.days.lost"
##  [7] "last.quarter.lost"          "last.year.lost"
##  [9] "last.three.years.lost"      "num.days.restrict"
## [11] "last.quarter.restrict"      "last.year.restrict"
## [13] "last.three.years.restrict" "num.death"
## [15] "last.quarter.death"         "last.year.death"
## [17] "last.three.years.death"     "num.dis"
## [19] "last.quarter.dis"           "last.year.dis"
## [21] "last.three.years.dis"       "viol.quantity"
## [23] "last.quarter.viol"          "last.year.viol"
## [25] "last.three.years.viol"
```

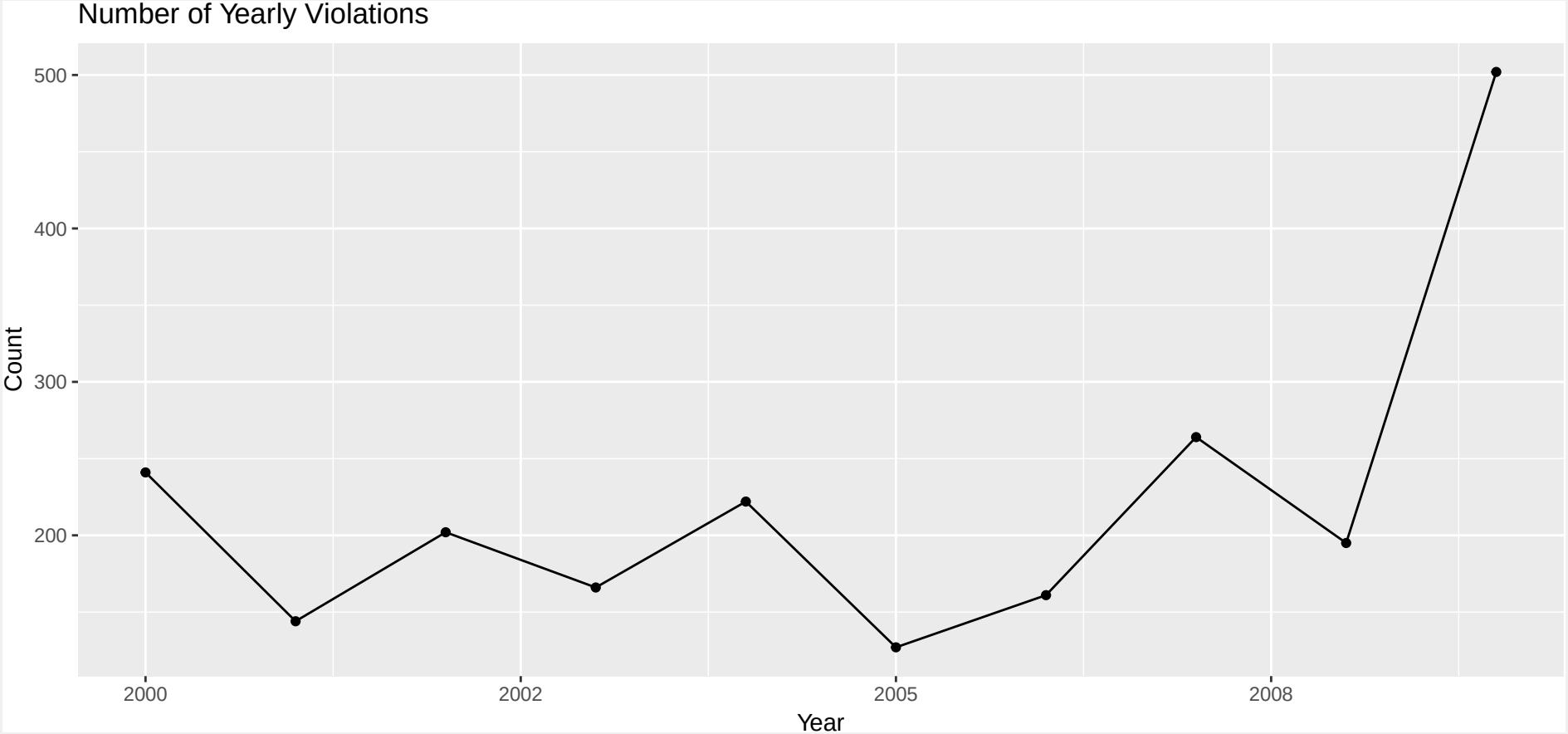
Top 10 Fatal Accidents Since 2005

- Query the consolidated data on the deadliest accidents

```
##                        mine.name mine_id year quarter num.death
## 1  Upper Big Branch Mine-South 4608436 2010       2         29
## 2                      Sago Mine 4608791 2006       1         12
## 3           Crandall Canyon Mine 4201715 2007       3          9
## 4                Darby Mine No 1 1518185 2006       2          5
## 5                    Gibson Mine 1202215 2007       3          3
## 6                  Affinity Mine 4608878 2013       1          2
## 7           Aracoma Alma Mine #1 4608801 2006       1          2
## 8        Black Stallion UG Mine 4609086 2014       2          2
## 9                  Cucumber Mine 4609066 2007       1          2
## 10               D-14 Stillhouse 1517165 2005       3          2
```

- Plot violation trends prior to disasters

Violation Trend: Upper Big Branch



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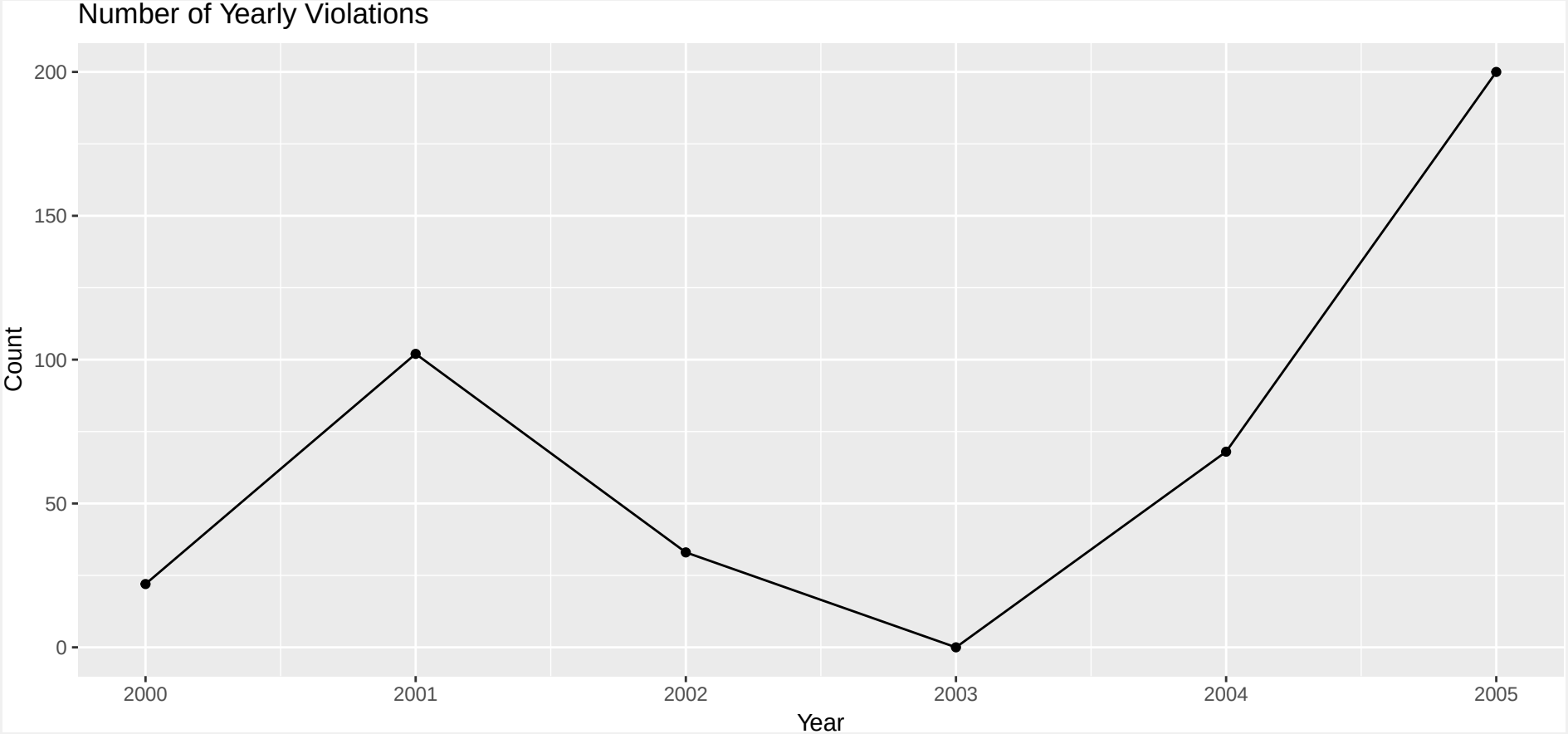
Violation Trend: Sago Mine



Predictive Model

- Rising violation trends before disasters
- Develop a disaster classifier based on historical data
- Define a **severe** accident as one with death or permenant disability

```
## # A tibble: 2 × 3
##   severe      n  perc
##    <lgl>  <int> <dbl>
## 1  FALSE 477077 99.46
## 2   TRUE   2608  0.54
```

Fixed-Mine Effects

- Biostatisticians and epidemiologists call it "conditional logistic regression" (`survival::clogit`)
- Suitable for **panel data** (e.g., longitudinal data, our consolidated data)
- Model includes mine-specific biases
- Logistic function (for every mine)

$$\Pr(Y = 1|\mathbf{X}) = \frac{1}{1 + e^{-(\alpha+\beta\mathbf{X})}}$$

- Logistic function with fixed effects (for the i-th mine)

$$\Pr(Y = 1|\mathbf{X}, i) = \frac{1}{1 + e^{-(\alpha_i+\beta\mathbf{x})}}$$

Logistic Regression Without Fixed Effects

- In-sample model

```
##            Reference
## Prediction  FALSE   TRUE
##      FALSE 477011   2600
##      TRUE      66      8
```

```
##    Accuracy Sensitivity Specificity   Precision          F1
##      0.9944      0.0031      0.9999      0.1081      0.0060
```

- Accuracy = (TP + TN)/(P + N)
- Sensitivity/recall = TP/P
- Specificity = TN/N
- Precision = TP/(TP + FP)
- F1: harmonic mean of sensitivity and precision

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Logistic Regression Without Fixed Effects

- Fails to predict top 10 deadliest disasters

```
##                        mine.name year quarter severe  pred
## 1  Upper Big Branch Mine-South 2010       2   TRUE FALSE
## 2                    Sago Mine 2006       1   TRUE FALSE
## 3         Crandall Canyon Mine 2007       3   TRUE FALSE
## 4              Darby Mine No 1 2006       2   TRUE FALSE
## 5                  Gibson Mine 2007       3   TRUE FALSE
## 6                 Affinity Mine 2013       1   TRUE FALSE
## 7          Aracoma Alma Mine #1 2006       1   TRUE FALSE
## 8       Black Stallion UG Mine 2014       2   TRUE FALSE
## 9                 Cucumber Mine 2007       1   TRUE FALSE
## 10             D-14 Stillhouse 2005       3   TRUE FALSE
```

Logistic Regression Without Fixed Effects

- List of false positive predictions based on predicted probability

```
##                                  mine.name year quarter severe pred
## 1  The American Coal Company New Era Mine 2008       3  FALSE TRUE
## 2  The American Coal Company New Era Mine 2008       2  FALSE TRUE
## 3  The American Coal Company New Era Mine 2007       4  FALSE TRUE
## 4  The American Coal Company New Era Mine 2008       4  FALSE TRUE
## 5  The American Coal Company New Era Mine 2008       1  FALSE TRUE
## 6  The American Coal Company New Era Mine 2009       1   TRUE TRUE
## 7  The American Coal Company New Era Mine 2007       3  FALSE TRUE
## 8  The American Coal Company New Era Mine 2006       1  FALSE TRUE
## 9  The American Coal Company New Era Mine 2005       4  FALSE TRUE
## 10 The American Coal Company New Era Mine 2006       2   TRUE TRUE
```

Logistic Regression with Fixed Effects

- Out-of-sample model (randomly select half of the data to train and the other half to test)

```
##            Reference
## Prediction  FALSE   TRUE
##      FALSE 141332    483
##      TRUE   97167    852
```

```
##    Accuracy Sensitivity Specificity   Precision          F1
##      0.5928      0.6382      0.5926      0.0087      0.0172
```

Logistic Regression with Fixed Effects

- Successfully predicts top 10 deadliest disasters

```
##                                mine.name year quarter severe pred
## 1                              Sago Mine 2006       1   TRUE TRUE
## 2                  Crandall Canyon Mine 2007       3   TRUE TRUE
## 3                       Darby Mine No 1 2006       2   TRUE TRUE
## 4                         Cucumber Mine 2007       1   TRUE TRUE
## 5                           Dotiki Mine 2010       2   TRUE TRUE
## 6                             Equality 2011       4   TRUE TRUE
## 7                           Meikle Mine 2010       3   TRUE TRUE
## 8                  Nanuuq Gold Project 2007       3   TRUE TRUE
## 9  4 J's Gravel Crushing Plant 2 2011       3   TRUE TRUE
## 10                             Adams 2006       3   TRUE TRUE
```

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Logistic Regression with Fixed Effects

- Still has a lot of false positive predictions
- List of false positive predictions based on predicted probability

```
##                                  mine.name year quarter severe pred
## 1  The American Coal Company New Era Mine 2006       1  FALSE TRUE
## 2             Upper Big Branch Mine-South 2009       3  FALSE TRUE
## 3             Upper Big Branch Mine-South 2009       1  FALSE TRUE
## 4             Upper Big Branch Mine-South 2006       4  FALSE TRUE
## 5             Upper Big Branch Mine-South 2005       1  FALSE TRUE
## 6  The American Coal Company New Era Mine 2005       3  FALSE TRUE
## 7  The American Coal Company New Era Mine 2008       1  FALSE TRUE
## 8  The American Coal Company New Era Mine 2007       4  FALSE TRUE
## 9             Upper Big Branch Mine-South 2006       1  FALSE TRUE
## 10            Upper Big Branch Mine-South 2006       3  FALSE TRUE
```

- What happened in the New Era Mine?

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New Era Mine

- Among the worst mines by number of days lost due to accidents

```
##                                    mine.name year quarter num.days.lost
## 1  The American Coal Company New Era Mine 2005       2           2940
## 2  The American Coal Company New Era Mine 2003       2           2914
## 3  The American Coal Company New Era Mine 2005       3           2874
## 4                                   Mathies 2002       1           2840
## 5  The American Coal Company New Era Mine 2004       3           2613
## 6  The American Coal Company New Era Mine 2004       1           2591
## 7                  Monongalia County Mine 2013       3           2563
## 8  The American Coal Company New Era Mine 2005       4           2487
## 9                    Powhatan No. 6 Mine 2013       1           2409
## 10                            Maple Creek 2001       1           2030
```

- Rising violation trend from 2000 to 2005

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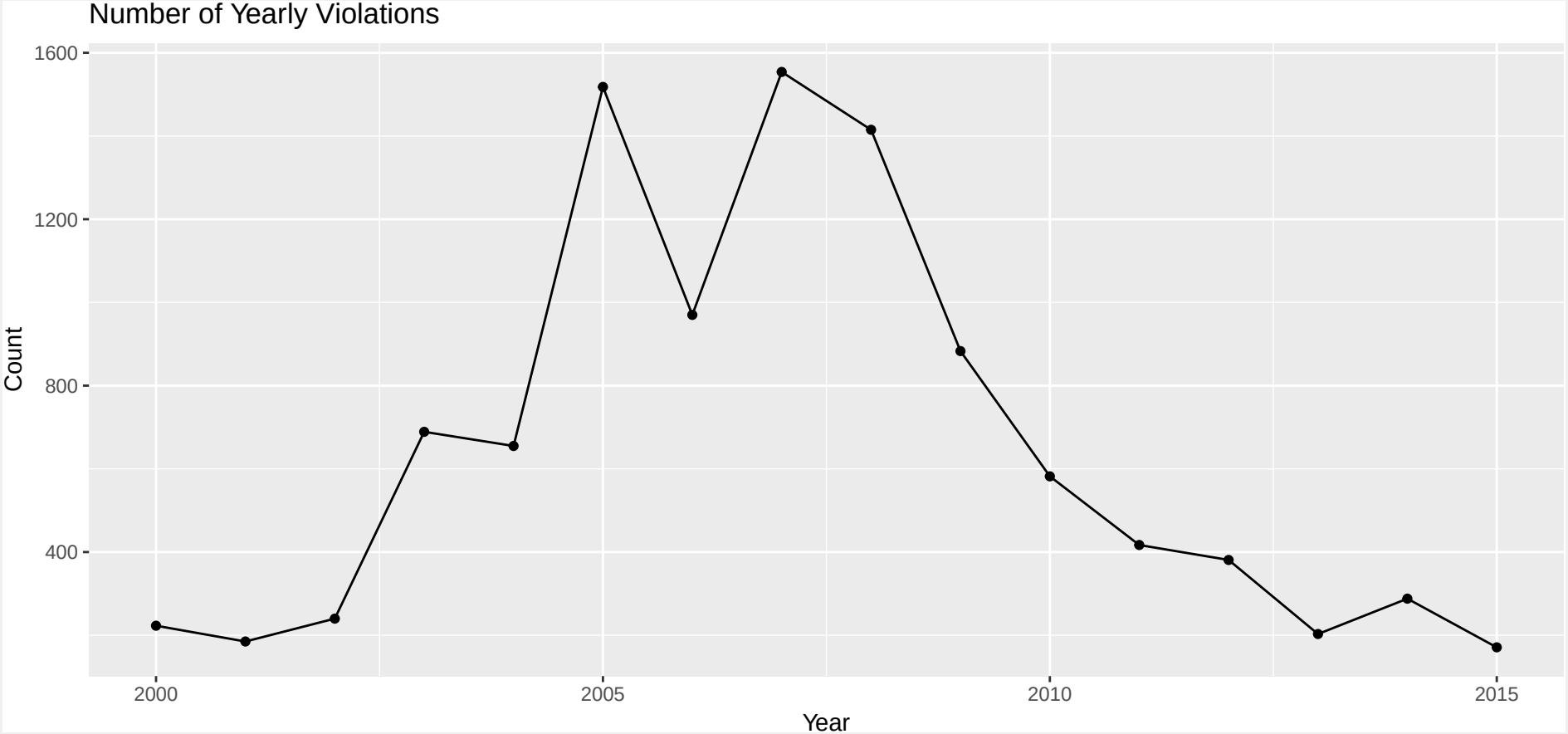
New Era Mine


Number of Yearly Violations
1600
1200
800
400
Count
2000
2005
2010
2015
Year

New Labels Including Days Lost

- Updated severe accident label
  - Previously defined criteria plus days lost > 300
- Redo out-of-sample model

```
##            Reference
## Prediction  FALSE   TRUE
##      FALSE 148496   1267
##      TRUE   88426   1645
```

```
##    Accuracy Sensitivity Specificity   Precision          F1
##       0.626       0.565       0.627       0.018       0.035
```

- Worse true positive rate, improved F1 score

New Labels Including Days Lost

- Successfully predicts 9 out of top 10 deadliest accidents

	mine.name	year	quarter	severe	pred
1	Sago Mine	2006	1	TRUE	TRUE
2	Crandall Canyon Mine	2007	3	TRUE	TRUE
3	Darby Mine No 1	2006	2	TRUE	TRUE
4	Cucumber Mine	2007	1	TRUE	TRUE
5	Dotiki Mine	2010	2	TRUE	TRUE
6	Equality	2011	4	TRUE	TRUE
7	Meikle Mine	2010	3	TRUE	TRUE
8	Nanuuq Gold Project	2007	3	TRUE	TRUE
9	4 J's Gravel Crushing Plant 2	2011	3	TRUE	TRUE
10	Adams	2006	3	TRUE	FALSE

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New Labels Including Days Lost

- Accidents of the New Era mine are now true positives

```
##                                    mine.name year quarter severe pred
## 1  The American Coal Company New Era Mine 2006       1   TRUE TRUE
## 2  The American Coal Company New Era Mine 2005       3   TRUE TRUE
## 3  The American Coal Company New Era Mine 2005       1   TRUE TRUE
## 4                  Monongalia County Mine 2014       3   TRUE TRUE
## 5                     Powhatan No. 6 Mine 2013       3   TRUE TRUE
## 6                     Powhatan No. 6 Mine 2013       4   TRUE TRUE
## 7                    Marshall County Mine 2015       4   TRUE TRUE
## 8  The American Coal Company New Era Mine 2008       1   TRUE TRUE
## 9                      Willow Lake Portal 2008       2   TRUE TRUE
## 10                    Powhatan No. 6 Mine 2013       1   TRUE TRUE
```

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Unsupervised Clustering

- Apply k-means clustering to consolidated data on all 20 features
- 3 clusters: `low`-risk, `mid`-risk, and `high`-risk
- Selected cluster centers (omitting 15 features)

```
##      num.days.lost num.days.restrict num.death num.dis viol.quantity
## low            5.3               2.1    0.0013  0.0029           2.6
## mid          100.5              18.6    0.0164  0.0313          34.3
## high         508.4              32.7    0.0431  0.0871          98.9
```

- Cluster sizes

```
##          low   mid high
## size 465203 13299 1183
```

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Markov Chain

- Overall transition matrix

```
##         low   mid  high
## low   0.997 0.003 0.000
## mid   0.087 0.906 0.006
## high 0.000 0.072 0.928
```

- Steady-state distribution

```
##        low   mid  high
## [1,] 0.97 0.028 0.003
```

Conclusion

- Summary
  - Two deadliest mine accidents in the last decade: Upper Big Branch & Sago
  - Rich MSHA data that need clean-up
  - Supervised predictive model
  - Unsupervised clustering of risk
- Application
  - "Credit score" for mine safety
  - Regulators, mines, stakeholders
- Future
  - Improve model performance
  - Expand data: OSHA, EPA, etc.
  - Artificial neural networks (restricted boltzmann machine), text mining, etc.

Appendix: Simple Linear Model

- Adjusted $R^2 = 0.36$

```
##                              Estimate Std. Error t value Pr(>|t|)
## (Intercept)                    0.5243    0.06725     7.8  6.4e-15
## last.quarter.lost              0.0566    0.00179    31.6 2.9e-218
## last.year.lost                 0.0724    0.00093    77.8  0.0e+00
## last.three.years.lost          0.0338    0.00032   105.6  0.0e+00
## last.quarter.restrict         -0.0173    0.00461    -3.8  1.7e-04
## last.year.restrict            -0.0123    0.00243    -5.1  3.9e-07
## last.three.years.restrict      0.0072    0.00085     8.4  3.8e-17
## last.quarter.viol              0.3083    0.01095    28.1 3.5e-174
## last.year.viol                 0.1352    0.00490    27.6 2.1e-167
## last.three.years.viol         -0.0346    0.00141   -24.7 4.2e-134
## last.quarter.death            -5.7149    1.09783    -5.2  1.9e-07
## last.year.death               -3.6943    0.64330    -5.7  9.3e-09
## last.three.years.death        -0.5155    0.33261    -1.5  1.2e-01
```