A Data-Driven Early Warning System for Mining Accidents

Yu Luo, Ashutosh Nanda, Shivaram Rajgopal, Vinay Ramesh, Zhizun Zhang, Catherine Zhao, and Venkat Venkatasubramanian

Chemical Engineering, Computer Science, and Business School
Columbia University

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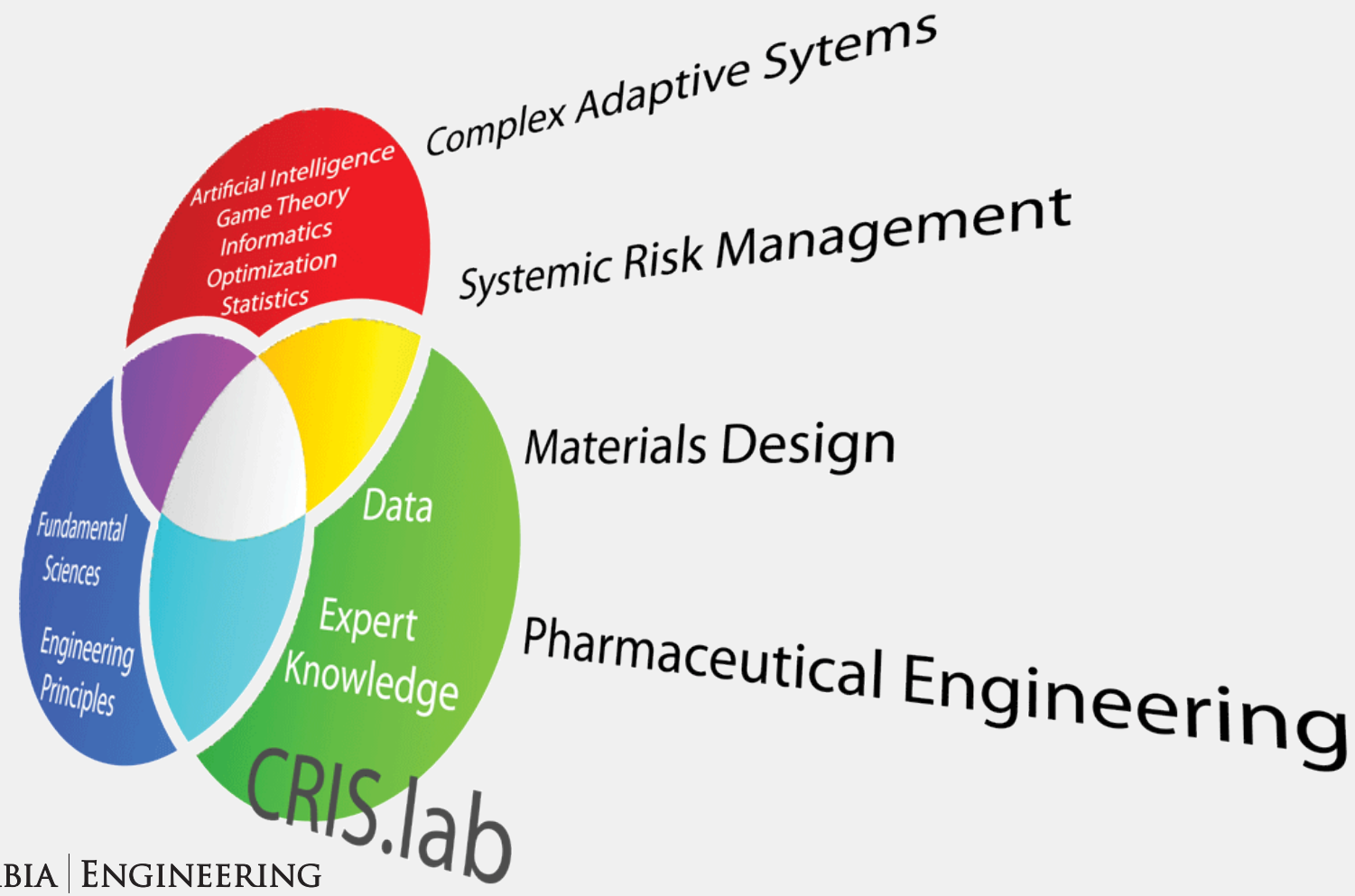
Complex, Resilient, Intelligent Systems (CRIS Lab)



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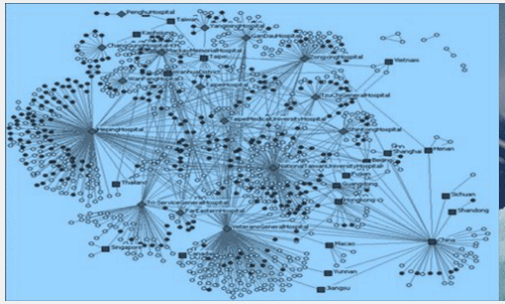
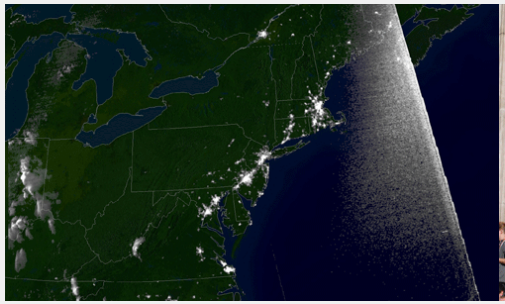
Systemic Risk

- Systemic disasters
  - SARS (2003)
  - Northeast Blackout (2003)
  - Subprime Crisis (2008)
  - Deepwater Horizon (2010)
- Emerging systemic risks
  - Climate change
  - Income/wealth inequality
  - Cyber-physical security
- Fast-paced and connected
- Prevent systemic disasters
- Go beyond one-off accidents







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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

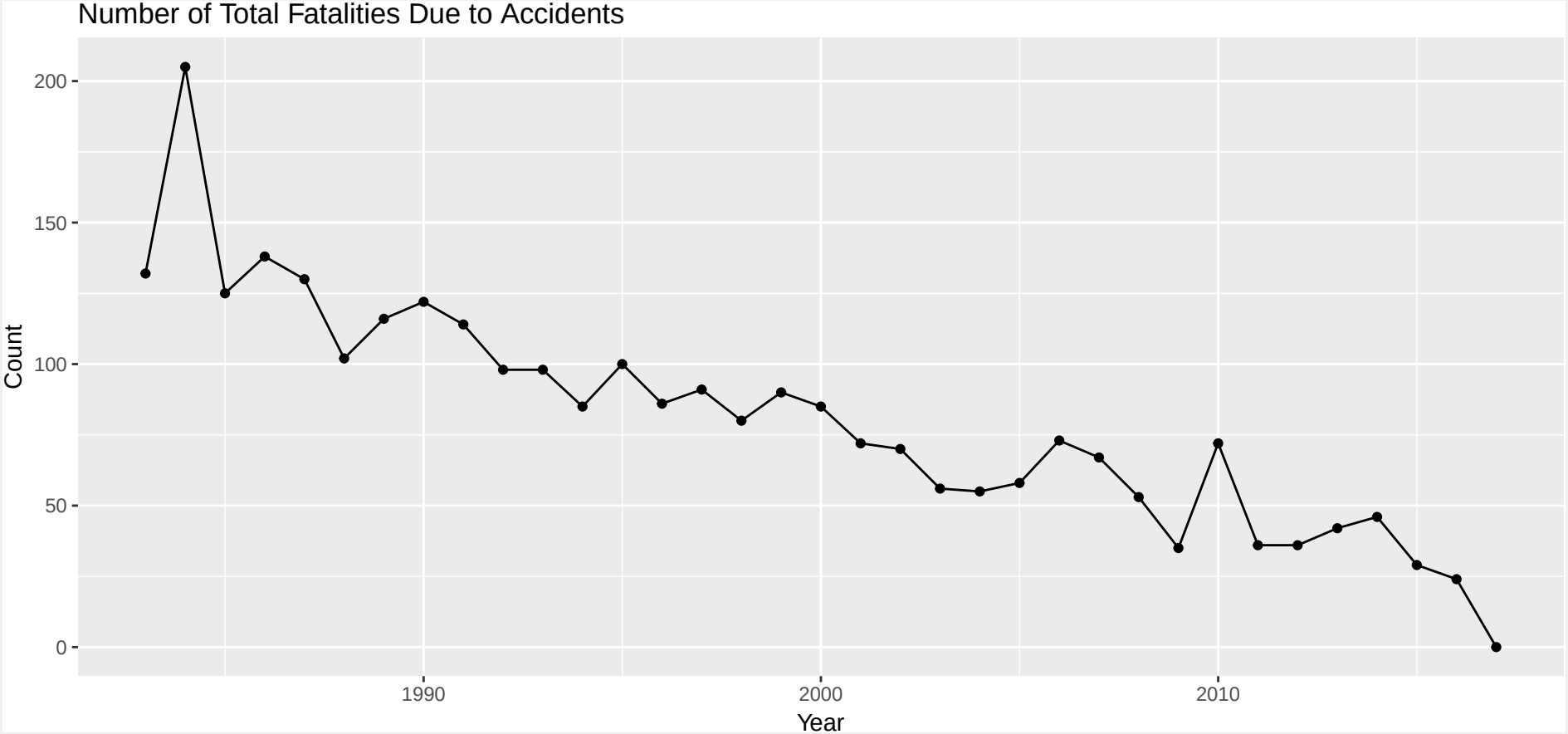
Sago Mine Disaster (2006)

- 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 U.S. 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"
```

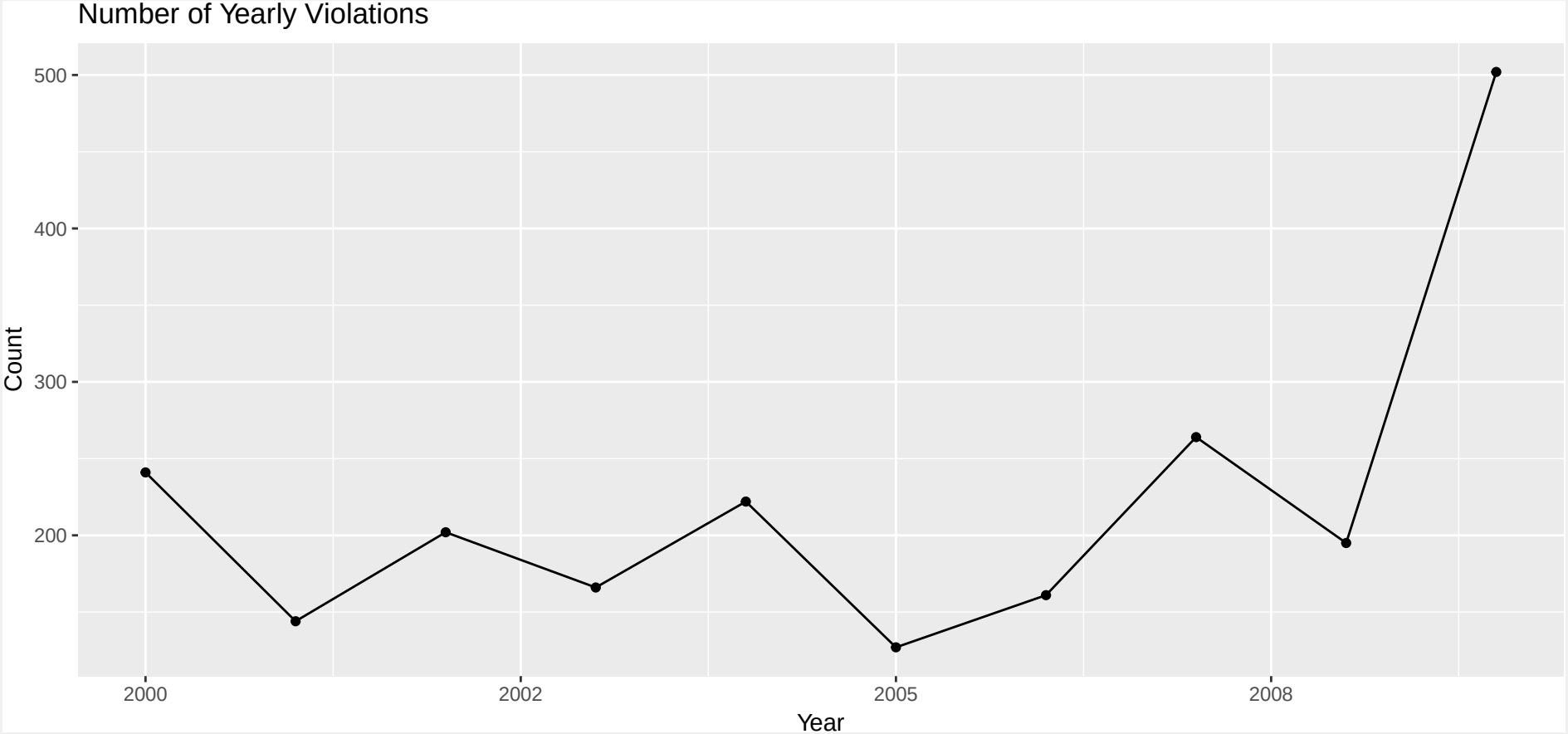
Top 10 Fatal Accidents Since 2005

- 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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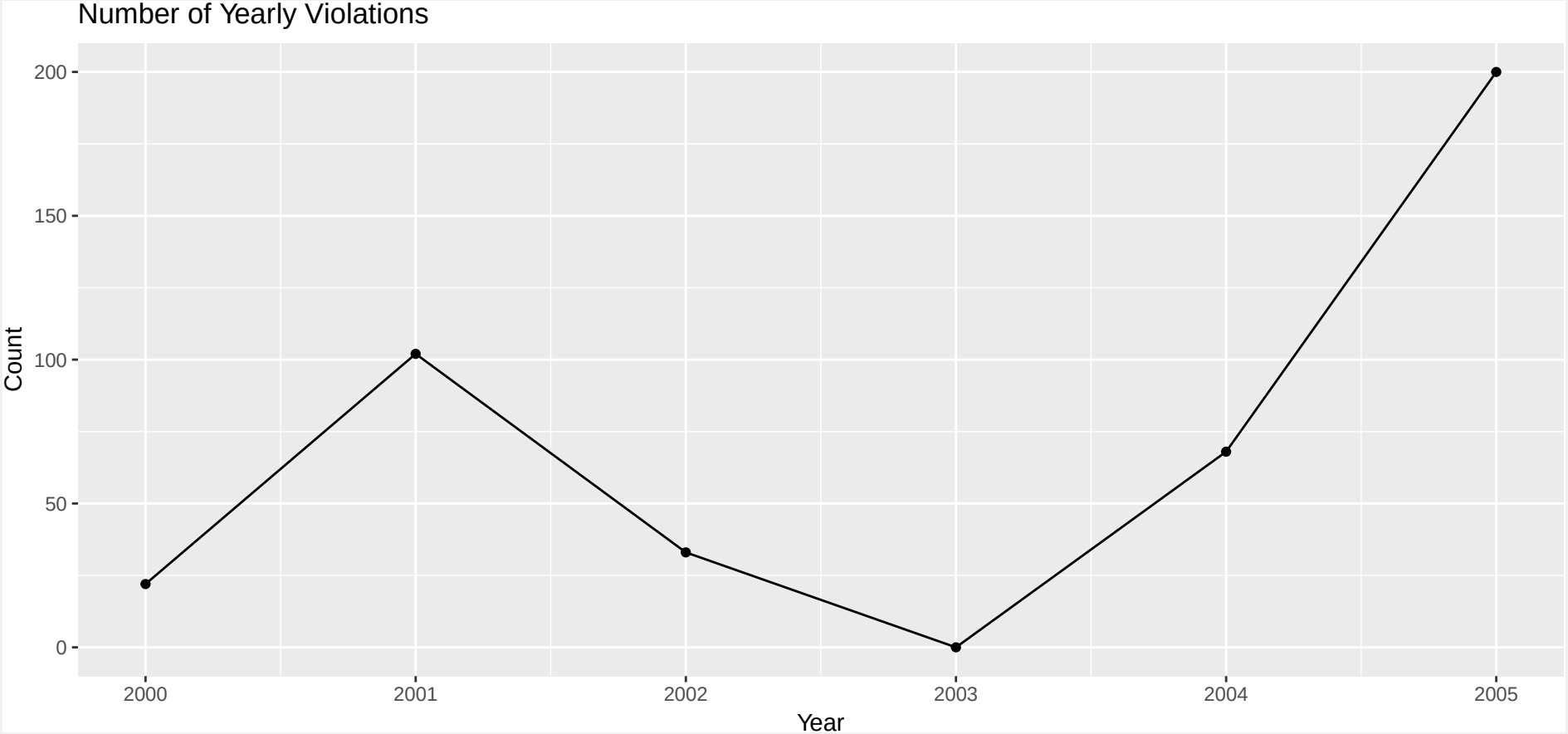
Violation Trend: Sago Mine



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)

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

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

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

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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
```

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?

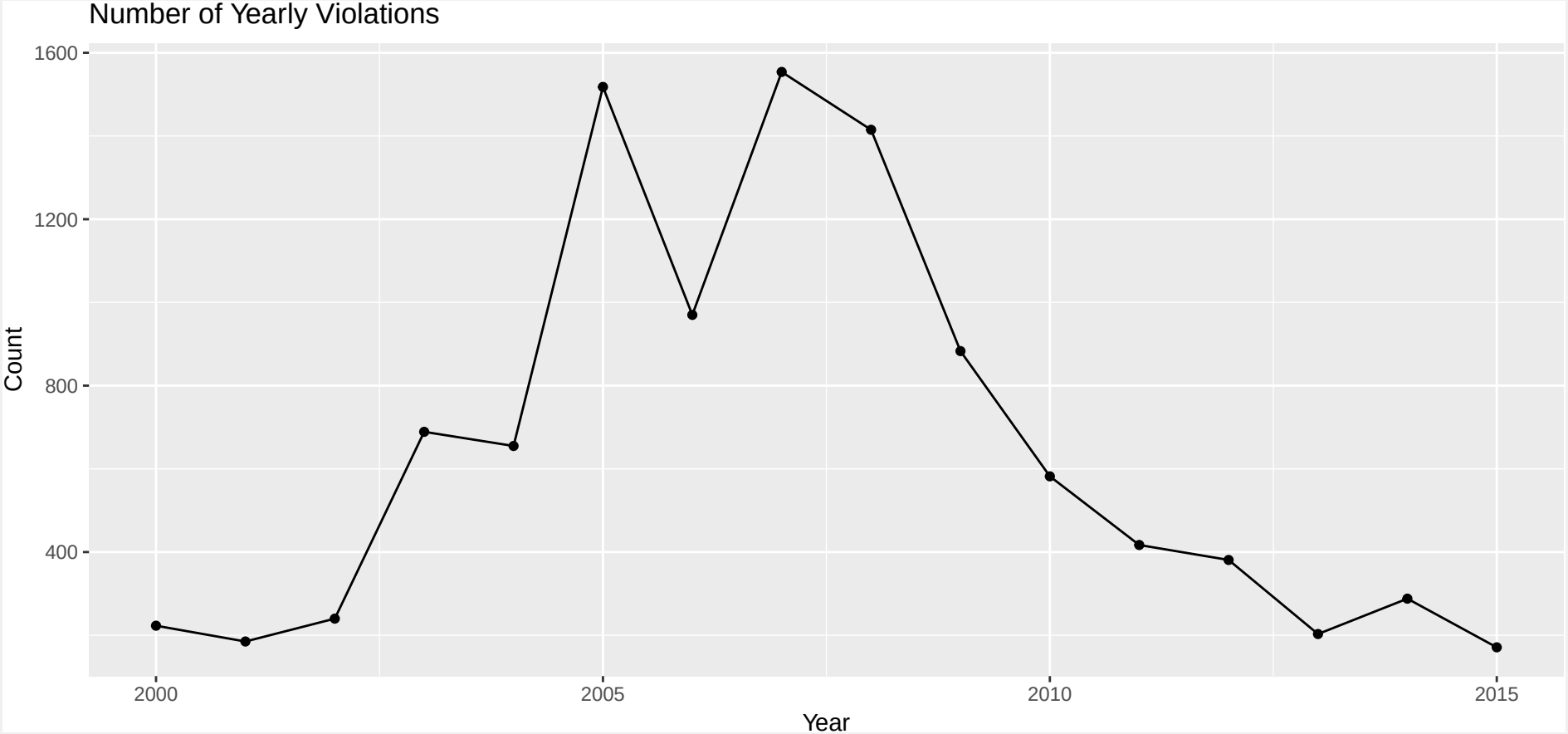
New Era Mine

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

```
##                                      mine.name year quarter 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

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
```

Conclusion

- Summary
  - Two deadliest mine accidents in the last decade: Upper Big Branch & Sago
  - Rich MSHA data that need clean-up
  - Supervised predictive model
- Application
  - "Credit score" for mine safety
  - Regulators, mines, stakeholders
- Future
  - Improve model performance
  - Unsupervised clustering, neural nets, etc.
  - Expand data: OSHA, EPA, 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
```

Appendix: 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 17 features)

```
##      num.days.lost num.days.restrict num.death
## low            5.3               2.1    0.0013
## mid          100.5              18.6    0.0164
## high         508.4              32.7    0.0431
```

- Cluster sizes

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

Appendix: 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
```