A Data-Driven Early Warning System for Mining Accident

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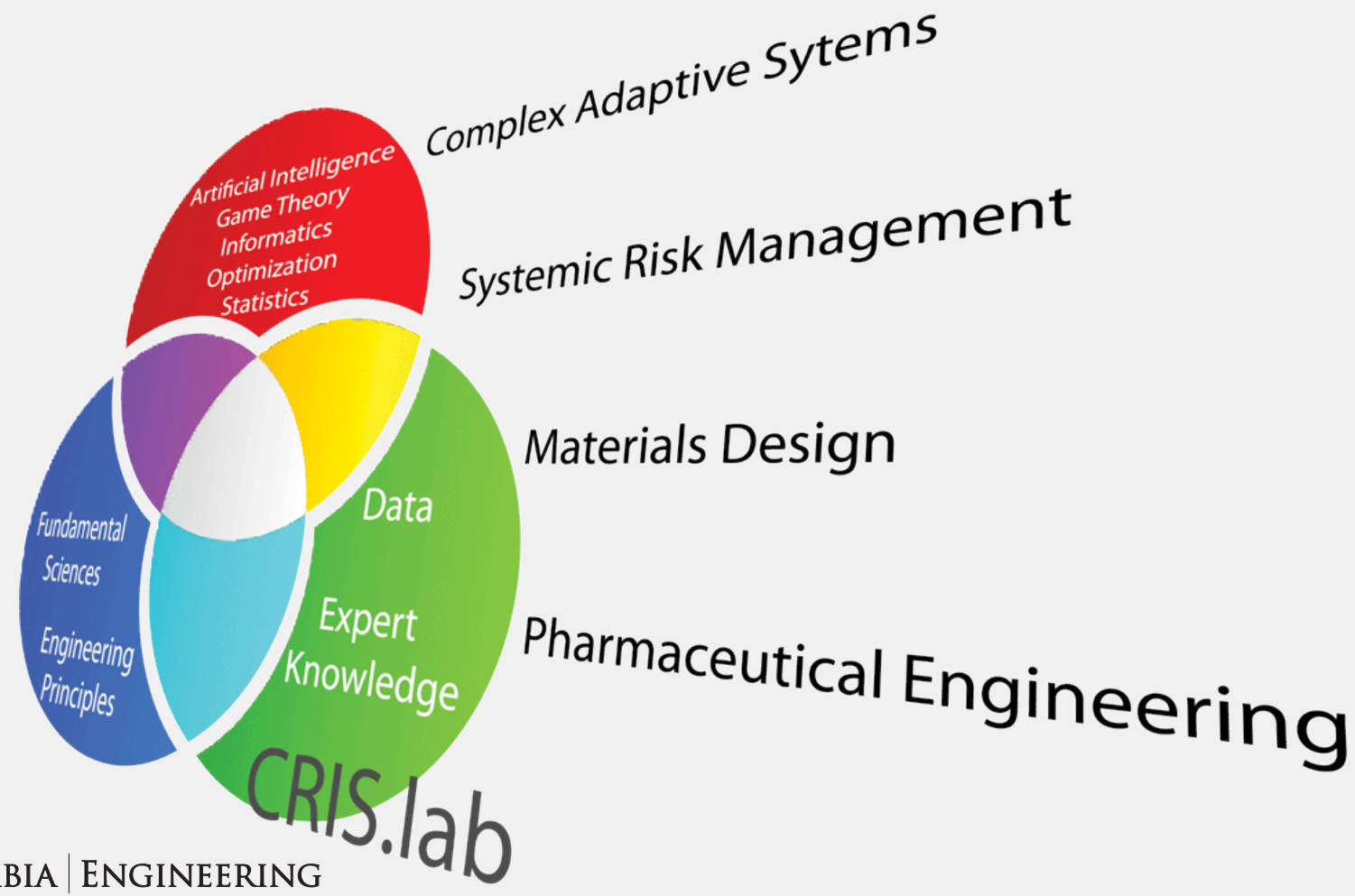
Complex, Resilient, Intelligent Systems (CRIS Lab)



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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

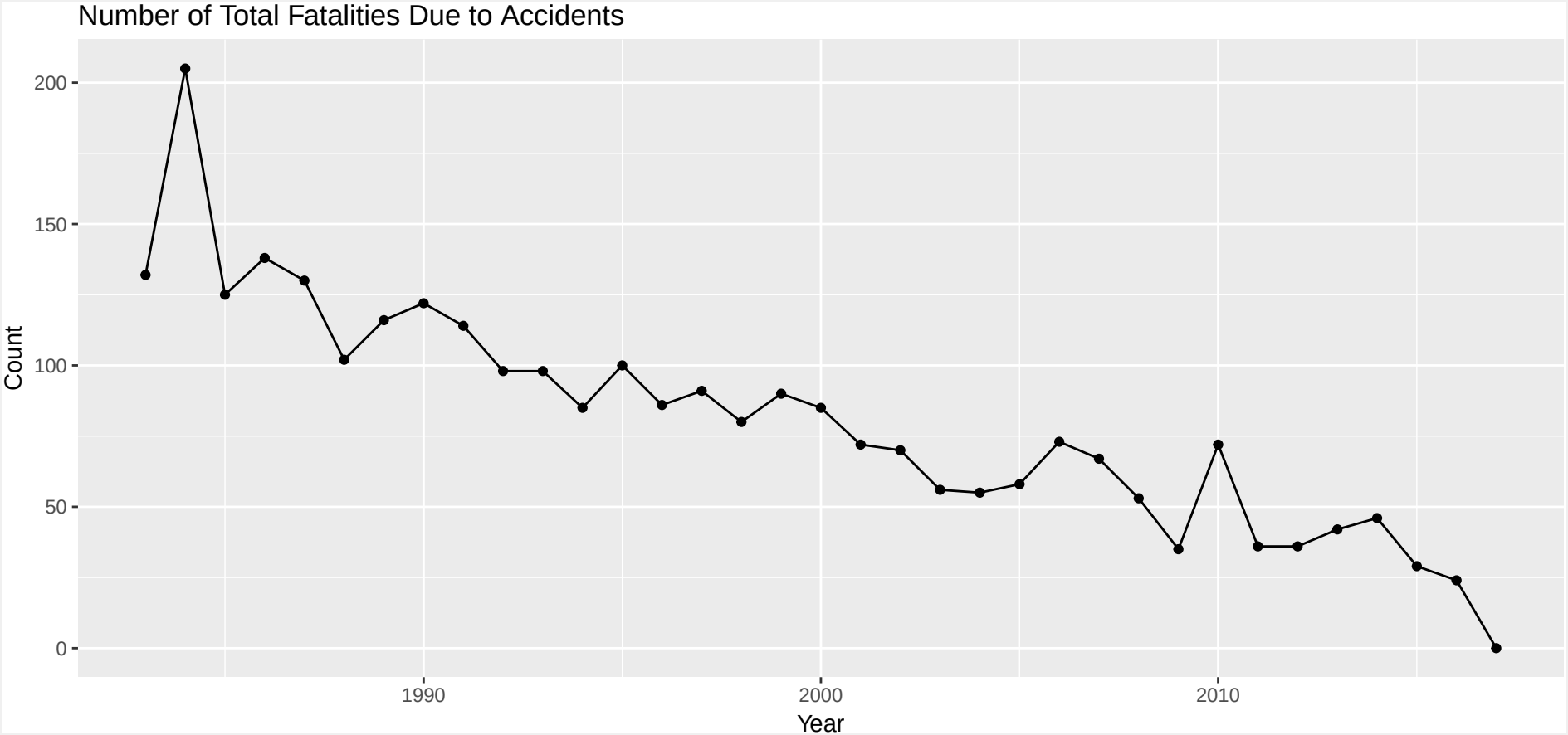
Sago Mine Disaster (2006)

- 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

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.

Department of Labor Enforcement Data

- Link: https://enforcedata.dol.gov/views/data_catalogs.php
- Updated daily or weekly
- Enforecement Data Catalog
  - MSHA Enforcement Data
  - OSHA Enforcement Data
  - EPA
  - FDA

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., selected attributes from the accidents table:

```
##  [1] "mine_id"          "controller_id"     "ai_dt"
##  [4] "inj_degr_desc"    "ai_class_desc"     "ai_occ_desc"
##  [7] "ai_acty_desc"     "exper_tot_calc"    "exper_mine_calc"
## [10] "exper_job_calc"   "ai_narr"           "cal_yr"
## [13] "cal_qtr"          "accident_type_cd"  "accident_type"
## [16] "no_injuries"      "occupation_cd"     "activity_cd"
## [19] "injury_source_cd" "injury_source"     "nature_injury_cd"
## [22] "nature_injury"    "inj_body_part_cd"  "inj_body_part"
## [25] "schedule_charge"  "days_restrict"     "days_lost"
## [28] "trans_term"       "return_to_work_dt" "immed_notify_cd"
## [31] "immed_notify"     "invest_begin_dt"   "closed_doc_no"
## [34] "coal_metal_ind"   "load_dt"           "ai_year"
```

MSHA Data: Challenges

- Missing data, typos
- Inactive mines are not labeled
- Most data are not numeric
- Relatively few severe accidents ($\sim 0.5\%$)

Consolidated Data

- Combine and summarize accidents/violations based on mines
- 664,128 rows, 10,377 unique mines
- From 2000 to 2015 in quarters
- 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

Consolidated Data

- Number of days lost (`num.days.lost`), numer of days restricted (`num.days.restrict`), number of deaths (`num.death`), number of permenant disabilities (`num.dis`), and number of violations (`viol.quantity`)

```
##  [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"
```

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Top 10 Fatal Accidents Since 2005

	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

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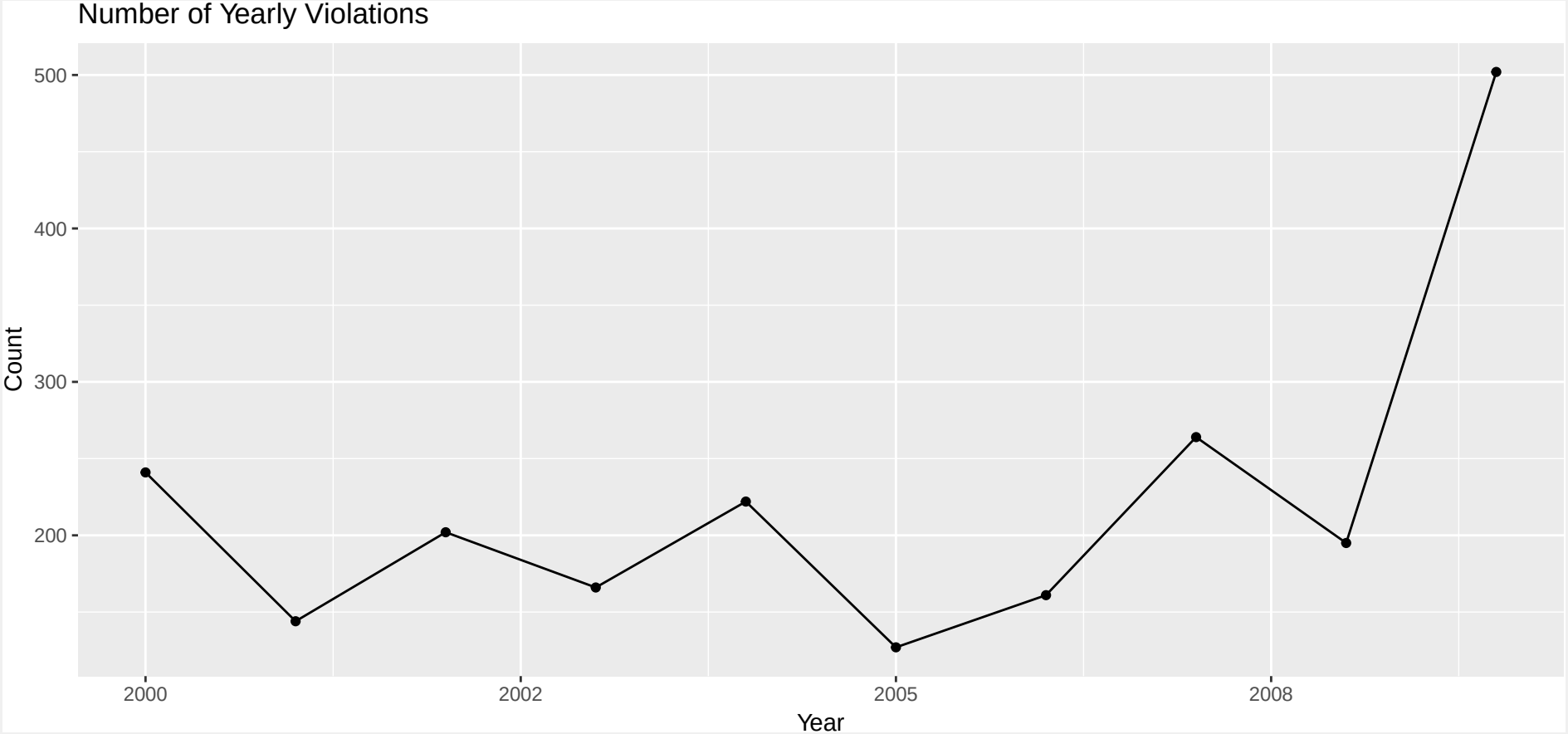
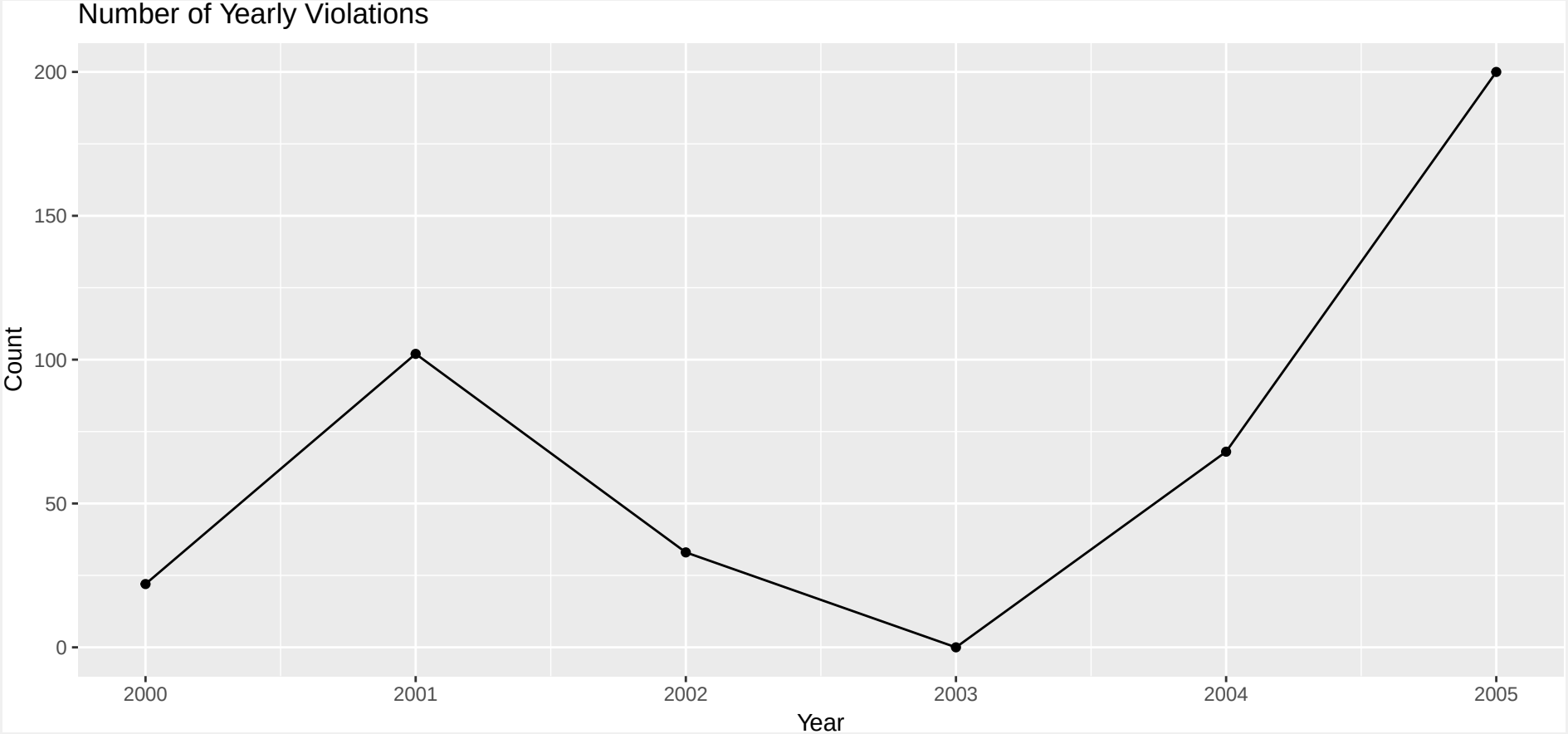
Violation Trend: Upper Big Branch



Violation Trend: Sago Mine



Predictive Model

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

```
## # 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., our consolidated data)
- Model includes mine-specific but time-invariant variables
- Logistic regression (for every mine)

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

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

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

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Logistic Regression Without Fixed Effects

- In-sample model

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

```
##          Sensitivity          Specificity       Pos Pred Value
##             0.003067             0.999862             0.108108
##       Neg Pred Value            Precision               Recall
##             0.994579             0.108108             0.003067
##                   F1            Prevalence       Detection Rate
##             0.005966             0.005437             0.000017
## Detection Prevalence    Balanced Accuracy
##             0.000154             0.501465
```

Logistic Regression Without Fixed Effects

- Fail to predict top 10 true positives

```
##                        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
```

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Logistic Regression Without Fixed Effects

- False positive predictions

```
##                                    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
```

```
##          Sensitivity          Specificity       Pos Pred Value
##               0.6382               0.5926               0.0087
##       Neg Pred Value            Precision               Recall
##               0.9966               0.0087               0.6382
##                   F1           Prevalence       Detection Rate
##               0.0172               0.0056               0.0036
## Detection Prevalence    Balanced Accuracy
##               0.4087               0.6154
```

Logistic Regression with Fixed Effects

- Successfully predict all top 10 true positives

```
##                                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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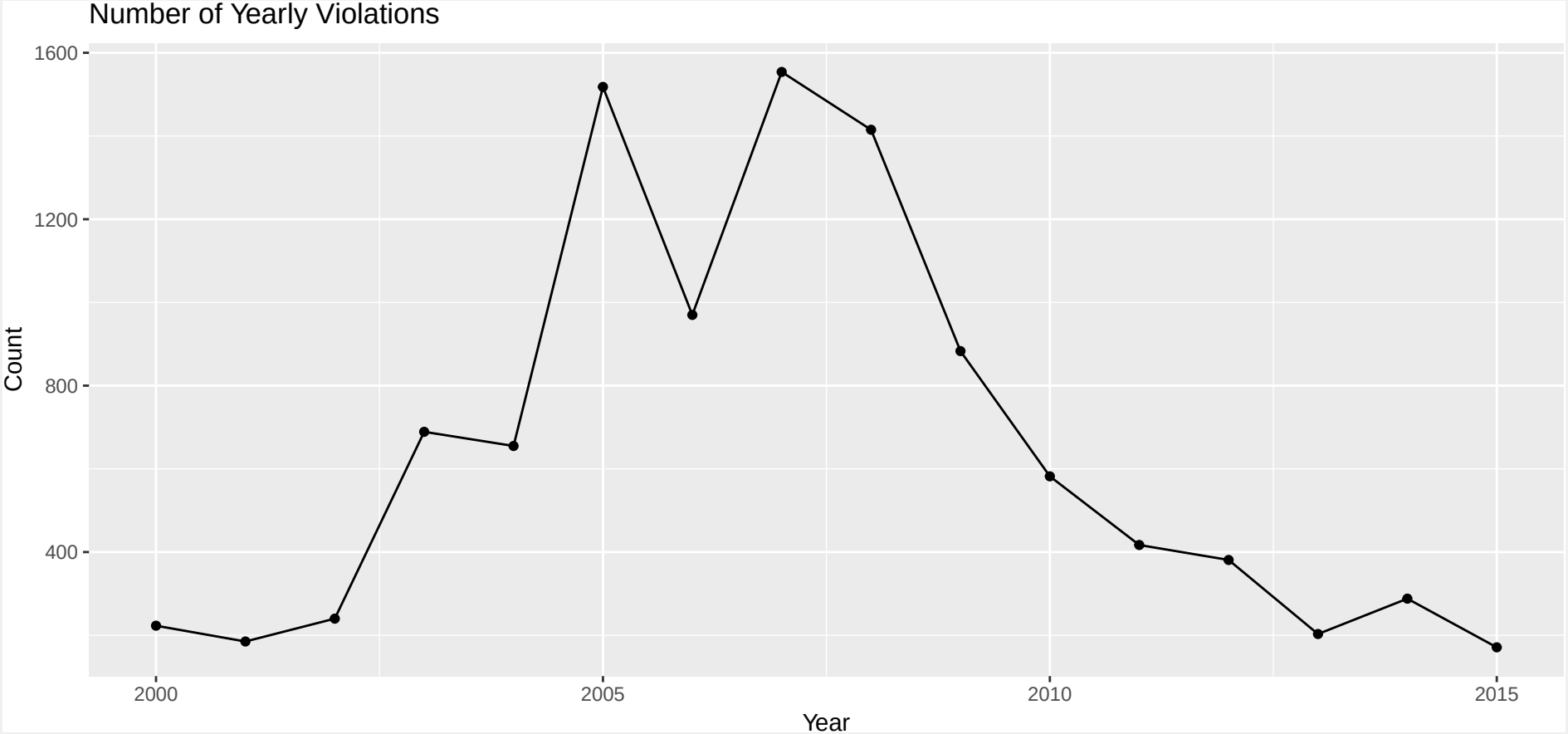
Logistic Regression with Fixed Effects

- False positive predictions

```
##                                  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
```

New Era Mine



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New Labels Including Days Lost

- Previously defined severe accidents and days lost > 300

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

```
##          Sensitivity          Specificity       Pos Pred Value
##               0.5649               0.6268               0.0183
##       Neg Pred Value            Precision               Recall
##               0.9915               0.0183               0.5649
##                   F1           Prevalence       Detection Rate
##               0.0354               0.0121               0.0069
## Detection Prevalence    Balanced Accuracy
##               0.3756               0.5958
```

New Labels Including Days Lost

- Successfully predict 9 out of top 10 true positives

```
##                                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

-

```
##                                    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

Markov Chain

Conclusion

- Summary
  - Two deadliest mine accidents in the last decade: Upper Big Branch & Sago
  - MSHA
- Application
  - "Credit score" for mine safety
  - Regulators, mines, stakeholders
- Future
  - Expand data: OSHA, EPA, etc.
  - Models and techniques: 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
```

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