

# A DATA-DRIVEN EARLY WARNING SYSTEM FOR MINING ACCIDENTS

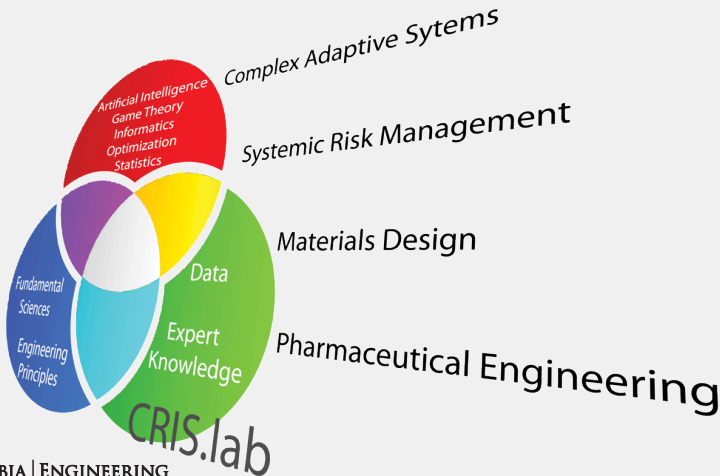
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- 1 MINE SAFETY: A DATA-DRIVEN APPROACH
- 2 METHODS: DATA SOURCES AND MODEL PRELIMINARIES
- 3 RESULTS AND DISCUSSION
- 4 CONCLUSION

# COMPLEX, RESILIENT, INTELLIGENT SYSTEMS (CRIS LAB)



# 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
- Prevent systemic disasters
- Analyze systemic risk: go beyond one-off accidents

# 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

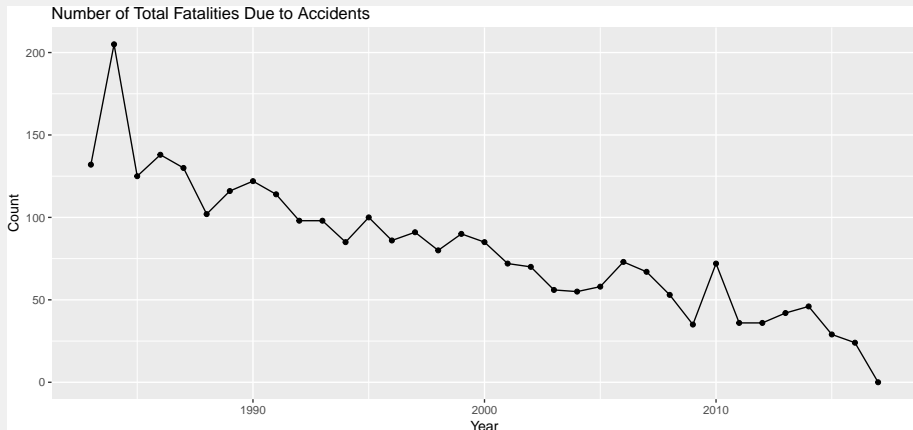
# SAGO MINE DISASTER (2006)

- 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](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](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

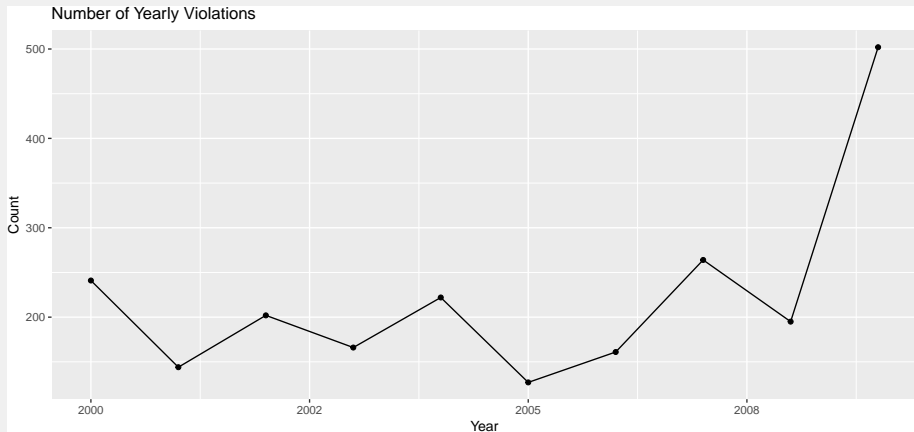
- Query the consolidated data on the deadliest accidents

##		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	

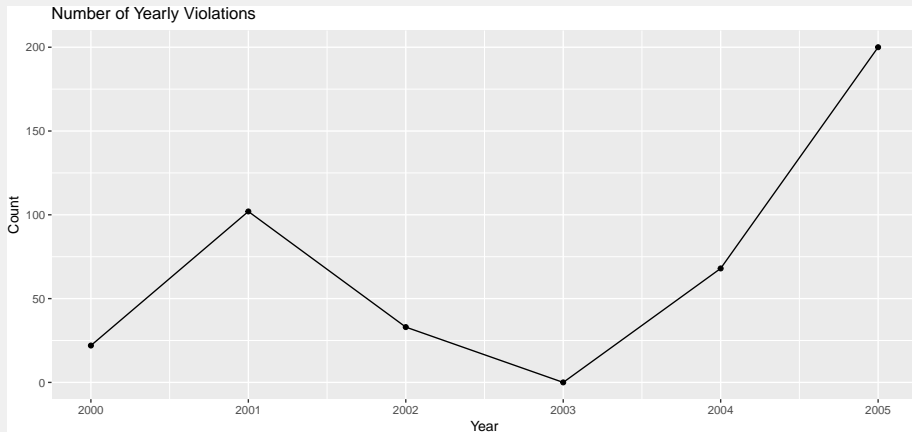
- Plot violation trends prior to disasters



# VIOLATION TREND: UPPER BIG BRANCH



# 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 permanent 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

■  $\text{Accuracy} = (\text{TP} + \text{TN}) / (\text{P} + \text{N})$

■  $\text{Sensitivity/recall} = \text{TP} / \text{P}$

■  $\text{Specificity} = \text{TN} / \text{N}$

■  $\text{Precision} = \text{TP} / (\text{TP} + \text{FP})$

■ F1: harmonic mean of sensitivity and precision

# 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?

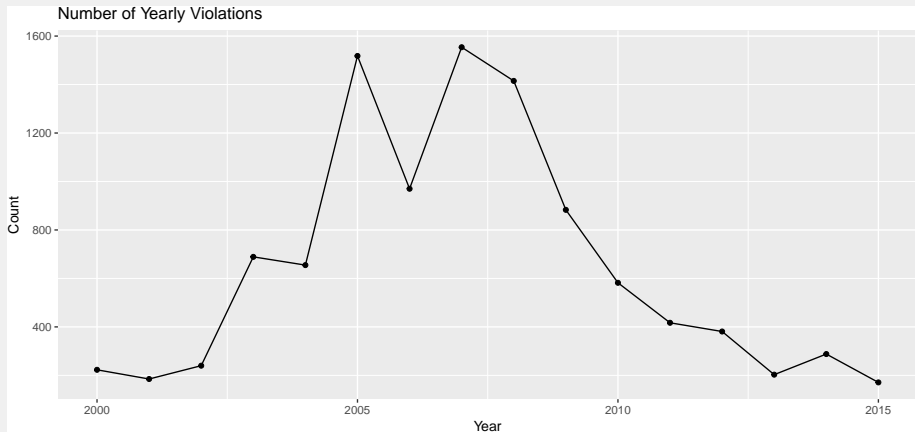
# NEW ERA MINE

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

##	mine.name	year	quarter	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

# NEW ERA MINE



# 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

# 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 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

# 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
```