Assessing Vulnerabilities in Software Systems: A Quantitative Approach

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Knowledge to Go Places

Presentation Outline

- Motivation and Background
- Vulnerability data and AML Vulnerability Discovery Model
  - Fitting HTTP Web servers' and Browsers' datasets
  - Measuring Prediction Capabilities
- Fitting categorized vulnerabilities
  - Categories
  - Severity Levels
  - Analyzing categorized vulnerabilities
- Conclusions and Future Work

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Motivation

- Security maintenance management
  - Security patch scheduling
  - Estimating the number of vulnerabilities
- Growing risk caused by software vulnerabilities
  - Loss estimation
  - Ownership cost estimation

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Research Objectives

- This research look into ways to estimate the number of potential vulnerabilities
- Providing users with:
  - Improving risk assessment
  - Comparison tools
  - Lay a foundation for stable metrics
- Providing developers with
  - Guidelines and tips for better development
  - Testing optimization tools
  - Improving software maintenance resource allocation

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Definition and Background

Definition: vulnerability is "a defect which enables an attacker to bypass security measures" [Schultz et al. 1990]

Related work:

- " [Rescorla 2005] and [Ozment 2005] applied some SRGMs to vulnerabilities
- Anderson suggested a model based on thermodynamics analogy
- Arbach et al. proposed a model for incidents

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Data Description

- Vulnerability Databases
  - National Institute of Standards and Technology's National Vulnerability Database, http://nvd.nist.gov
  - MITRE Corporation, http://www.mitre.org
- Defects Data
  - Vendors
  - Bugzilla, http://www.bugzilla.org
  - Independent Articles
- Market share
  - Google (until mid-2004)
  - Internet counters
- Software sizes
  - Vendors
  - Experts

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Vulnerability Datasets

- Operating Systems
  - Windows and Red Hat Linux
- Web-servers
  - Microsoft IIS and Apache
- Web-browsers
  - Internet Explorer and Fire Fox

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Vulnerability Discovery Models

- Security and reliability analogy
- VDMs and SRGMs analogy
- Characterizing security
  - Number of potential vulnerabilities
  - Vulnerability discovery rate

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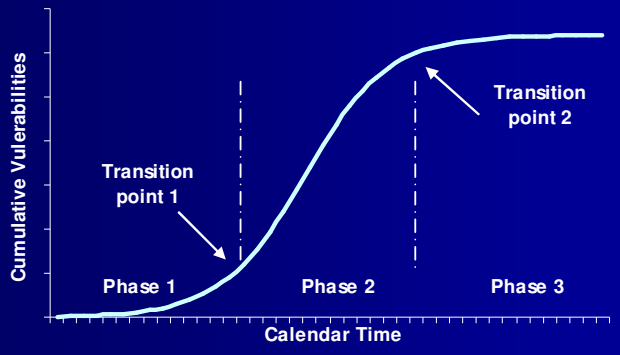
The Logistic Model

- A time-based model

$$\Omega(t) = \frac{B}{BCe^{-ABt} + 1}$$



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The Linear Model

- Approximation of the logistic model
- The learning phase may be very brief
- Significant number of vulnerabilities are still present and continue to be found
- The dataset is a superimposition of two or more consecutive S-shaped models $\Omega(t) = (S \times t) + k$

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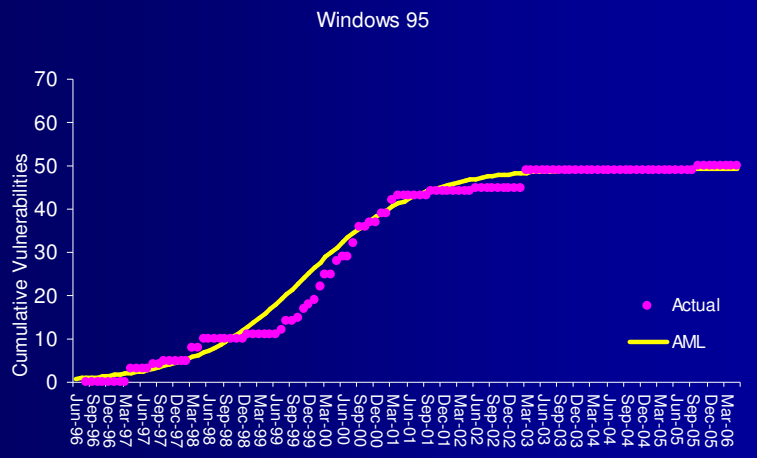
Validating The Logistic Model



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Goodness of fit test-AML

System	A	B	C	DF	χ^2	$\chi^2_{critial}$ (5%)	P-value	Fit Result
Win 95	0.001652	49.5512	1.32092	132	45.748	159.8135	1	*Significant*
Win 98	0.000522	92.6789	0.10233	92	107.001	115.3898	0.135785	*Significant*
Win XP	0.000232	280.513	0.09994	59	54.6261	77.93052	0.637299	*Significant*
Win NT 4.0	0.000317	184.78	0.44439	140	267.173	168.613	0	Insignificant
Win 2000	0.0001096	391.984	0.0386	79	95.1500	100.7486	0.104079	*Significant*
R H Linux 6.2	0.000855	121.235	0.13973	75	36.19688	96.21667	0.999956	*Significant*
R H Linux 7.1	0.169437	166.735	0.29531	65	39.6227	84.82064	0.99456	*Significant*
Red Hat Fedora	0.002014	139.045	0.53497	31	31.81382	44.98534	0.425800	*Significant*
Solaris 7.0	0.000526	126.32	0.11076	95	107.701	118.7516	0.1759	*Significant*
Solaris 8.0	0.000961	99.815	0.26380	80	69.7045	101.8795	0.7877	*Significant*
Solaris 9.0	0.000528	114.25045	0.11979	52	34.964	69.83216	0.9665	*Significant*

The Effort-Based Model

- Data needed: The total effort spent using the software system
  - Percentage of market share
  - Global internet population
  - Effort is calculated: $E = \sum_{i=0}^{n} (U_i \times P_i)$
- The effort is mapped to the vulnerability datasets by eliminating the time
- The effort/vulnerabilities data is fitted to the model:

$$\Omega(E) = B(1 - e^{-\lambda_{vu} E})$$

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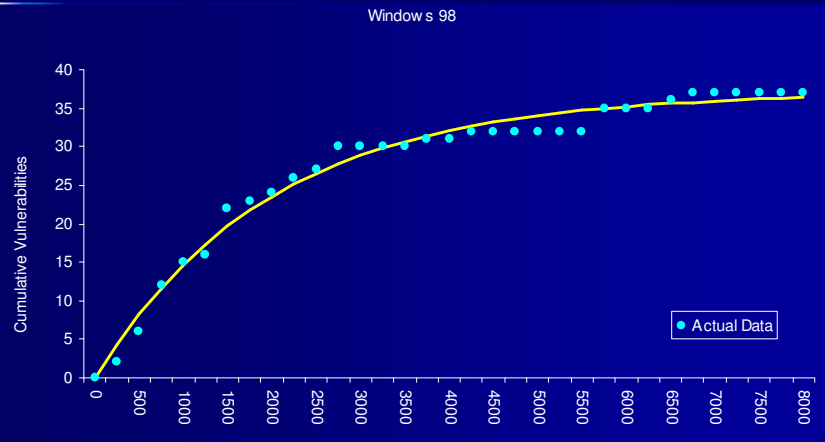
Validating The Effort-Based Model



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Web Servers Datasets Overview

- Apache and IIS market share (90.6%)

	Apache		IIS		SJSWS (SunOne)	Zeus
First Release	1995		1995		2002	1995
Market Share	69.7%		20.92%		2.53%	0.78%
Version	**1.x**	**2.x**	**4.0**	**5.0**	Up to 6.1	Up to 4.3
Vulnerabilities	58	45	85	73	3	5

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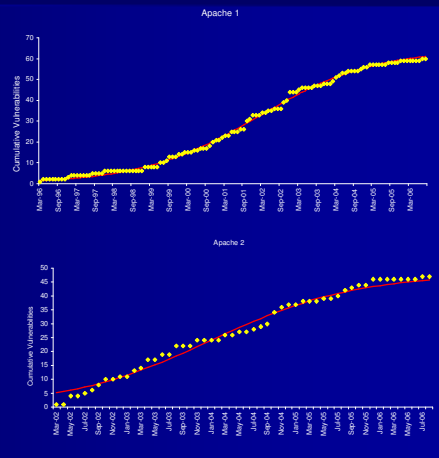
Web servers Datasets Goodness of Fit Test

Software Sys	Fit
Apache 1.x	*Significant*
Apache 2.x	*Significant*
IIS 4.x	*Significant*
IIS 5.x	*Significant*



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Web Browsers Datasets Overview

Web Browser	IE	Firefox	Mozilla	Safari	Other
Market Share	85.2%	9.6%	0.37%	3.06%	1.77%
Vulnerabilities	265	94	38	24	N/A
Release Date	Aug 95	Sep 02	Dec 98	Jan 03	N/A

Browser	Nov 2004	Apr 2005	Jan 2006	Jul 2006
IE	88.9%	86.63%	85.82%	83.05%
Firefox	4.58%	8.69%	11.23%	12.93%

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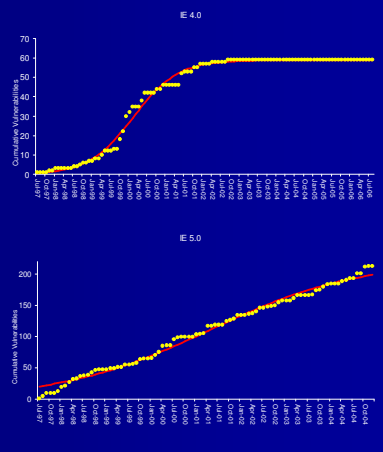
Web Browsers Datasets Goodness of Fit Test

Software Sys	Significant
IE 4.0	*Significant*
IE 5.0	*Significant*
IE 6.0	Insignificant
FFox1.0	Insignificant
FFox1.5	*Significant*



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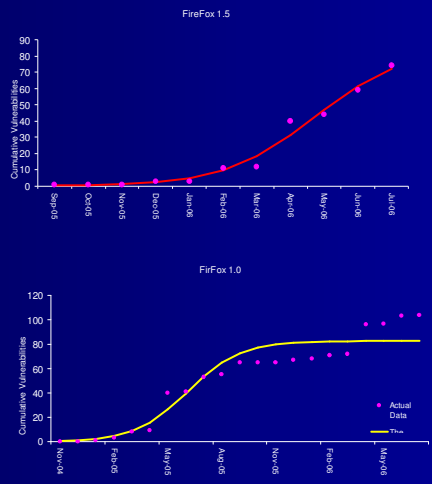
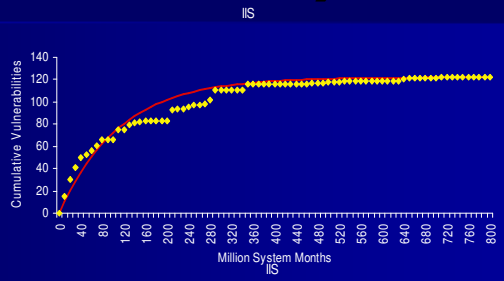
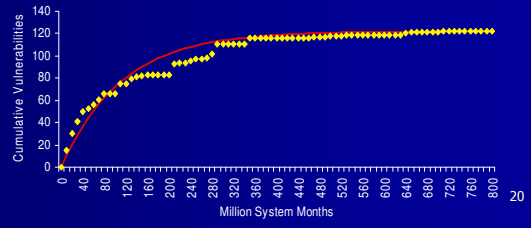
Web Browsers Datasets Goodness of Fit Test



Goodness of Fit Results (Effort-Based Model)

	Significance
Apache	*Significant*
IIS	*Significant*





Goodness of Fit Results

- AML model fits the datasets
  - The superposition effect: Consecutive S-shaped models because of shared vulnerabilities
- Effort-based model fits the datasets

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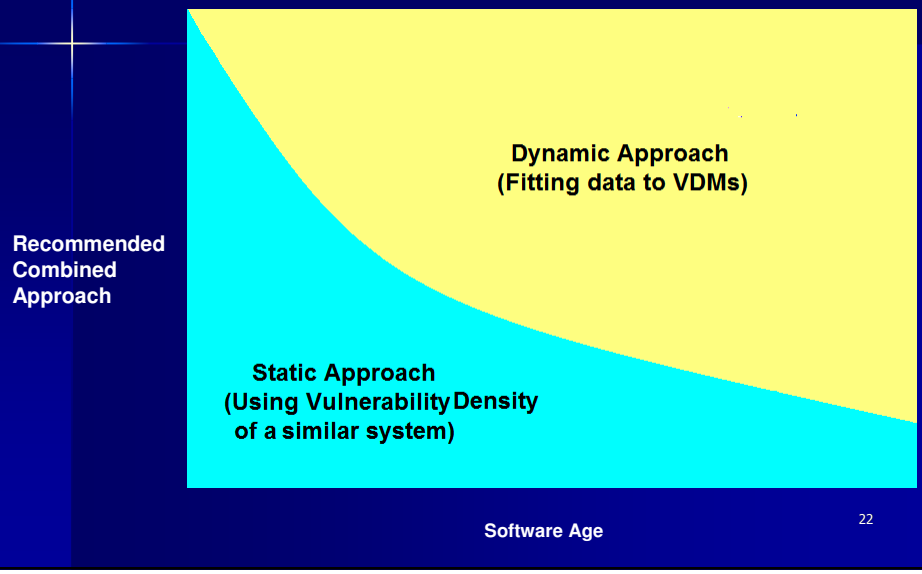
Prediction Approaches



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Vulnerabilities Taxonomy

- Input Validation Error (IVE) (Boundary condition error (BCE), Buffer overflow (BOF)):
  - Include failure to verify the incorrect input and read/write involving an invalid memory address.
- Access Validation Error (AVE):
  - These vulnerabilities cause failure in enforcing the correct privilege for a user.
- Exceptional Condition Error Handling (ECHE):
  - May arise due to failures in responding to unexpected data or conditions.
- Environmental Error (EE):
  - Triggered by specific conditions of the computational environment.

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Vulnerabilities Taxonomy

- Configuration Error (CE):
  - These vulnerabilities result from improper system settings.
- Race Condition Error (RC):
  - These are caused by the improper serialization of the sequences of processes.
- Design Error (DE):
  - These are caused by improper design of the software structure.
- Others:
  - Includes vulnerabilities that do not belong to the types listed above, sometimes referred to as nonstandard.

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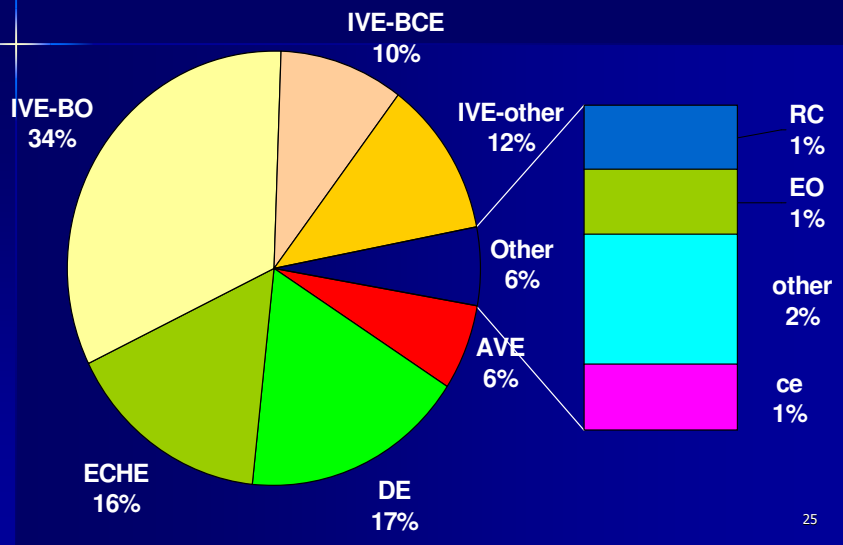
Windows XP



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Goodness of Fit Results

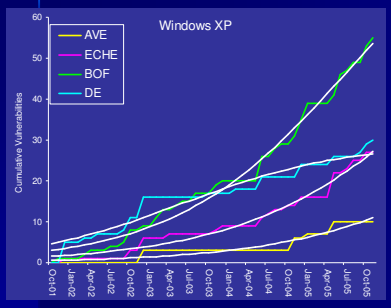
Windows 2000

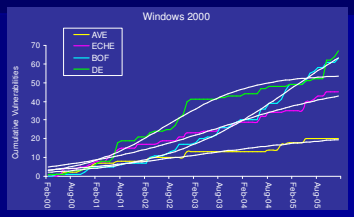
Vulnerability Type	Parameters			X^2		
	A	B	C	P-value	X^2	X^2 Critical
AVE	0.002121	23.181	0.279309	*1*	25.5528	92.81
ECHE	0.001026	51.954	0.189765	*0.99956*	38.63088	
BOF	0.000676	93.862	0.495049	*1*	19.62047	
DE	0.001791	54.358	0.343025	*0.99448*	45.14116	

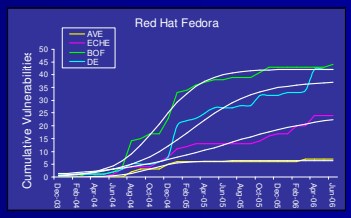
Windows XP

Vulnerability Type	Parameters			X^2		
	A	B	C	P-value	X^2	X^2 Critical
AVE	0.001035	63.595	2.0119	*1*	17.70871	67.50
ECHE	0.000700	92.864	0.674	*1*	12.10664	
BOF	0.000808	93.578	0.348	*1*	14.82454	
DE	0.002854	28.984	0.1958	*1*	13.08505	

OS: Vulnerability Categories







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Severity Levels

- Common Vulnerabilities Scoring System: A 10 points system to measure the risk of the vulnerabilities
  - High (7-10)
  - Medium (4-6.99)
  - Low (1- 3.99)

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Modeling Vulnerabilities by Severity

Apache

Vulnerability Severity Level	Parameters			X^2		
	A	B	C	P-value	X^2	$X^2_{Critical}$
High	.00156	27.00	1.00	1	42.1	144.3
Low	.00248	18.00	1.76	1	15.7	

IIS

Vulnerability Severity Level	Parameters			X^2		
	A	B	C	P-value	X^2	$X^2_{Critical}$
High	.00176	38	.999	1	28.2	133.2
Low	.00127	77.9	1.21	.999	53.5	

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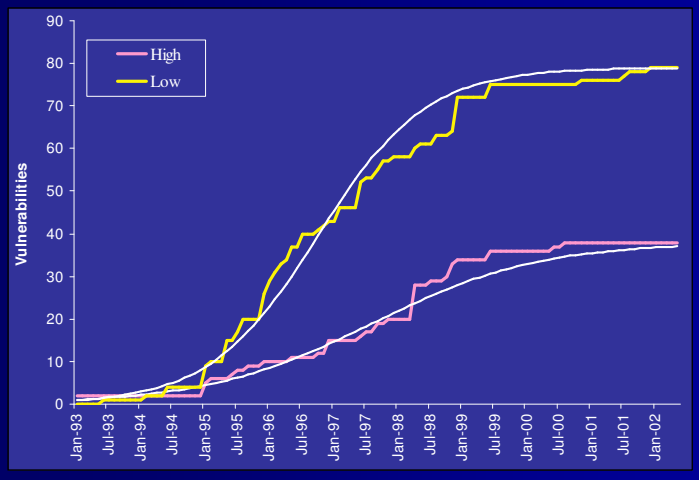
Modeling Vulnerabilities by Severity

IIS



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Categories vs. Severity level

Apache

	AVE	DE	ECHE	IVE BOF	IVE BCE	IVE other	RC	EE	CE	other	Total
High	3	5	3	7	1	10	0	3	2	1	35
Medium	0	1	1	3	0	0	1	0	0	0	6
Low	3	17	***12***	3	1	14	1	1	***12***	4	68
Total	6	23	16	13	2	24	2	4	14	5	109

Windows 2000

	AVE	DE	ECHE	IVE BOF	IVE BCE	IVE other	RC	EE	CE	other	Total
High	10	29	12	***52***	18	7	1	2	4	1	135
Medium	6	15	2	5	0	2	0	0	2	1	33
Low	6	26	***32***	9	3	16	1	2	3	1	100
Total	22	70	46	66	21	25	2	4	9	3	268

Results Summary

- Buffer overflow
  - Linked to high severity vulnerabilities
- Exceptional Control Handling Error
  - Linked to low severity vulnerabilities
- Input Validation errors
  - Vulnerabilities of this type other than Buffer overflow and boundary condition error has also shown to be linked to low severity vulnerabilities
- Design Error vulnerabilities
  - found to be a significant category of which a significant proportion is usually of high severity

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Summary

- The AML was validated on systems, web servers and web browsers
- The Effort-based model was validated on web server's datasets
- The prediction capabilities were tested
- Several estimation approaches were suggested

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Summary

- Constrained version of AML model was suggested
- Prediction capability is comparable to SRGMs
- Categorized vulnerabilities has been analyzed
- The AML was fitted to categorized data
- Some severity levels has shown strong relationship with some vulnerability categories

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Future Work

- White Box analysis
  - Identifying vulnerable modules
  - Analyzing the impact of the code reuse
- Studying the impact of patches
  - what happens after a major patch is applied (e.g. SP1, SP2)?

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Future Work

- Evaluating the vulnerabilities economical impact
  - Incentives for vulnerabilities finders
- Real-time quantitative risk assessment using
  - Vulnerabilities and incidents
- Using Testing-oriented categorization of vulnerabilities

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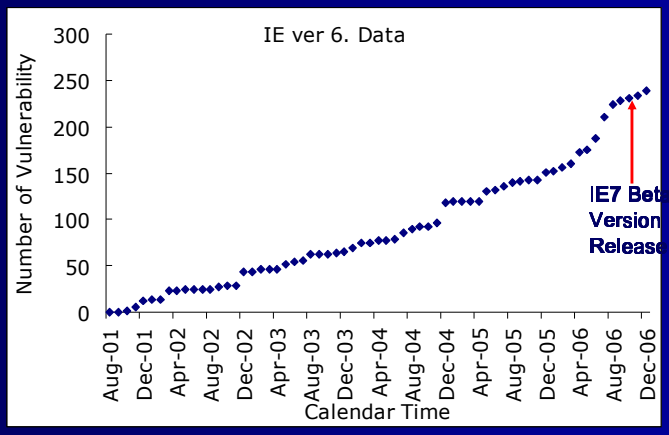
Beta test version effect



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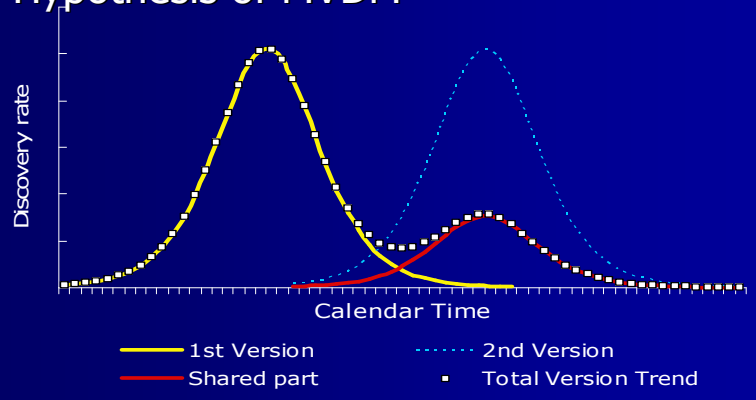
Multiple Vulnerability Discovery Model (MVDM)

- Hypothesis of MVDM



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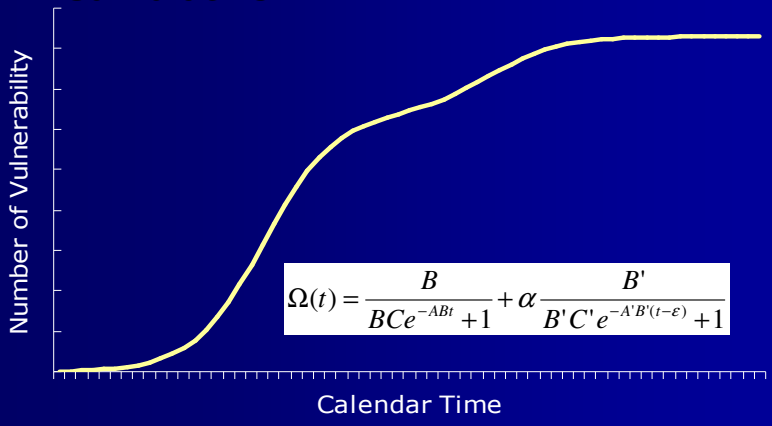
Multiple Vulnerability Discovery Model (MVDM) – Cont.

- Cumulative MVDM



$$\Omega(t) = \frac{B}{BCe^{-ABt}+1} + \alpha\frac{B'}{B'C'e^{-A'B'(t-\varepsilon)}+1}$$

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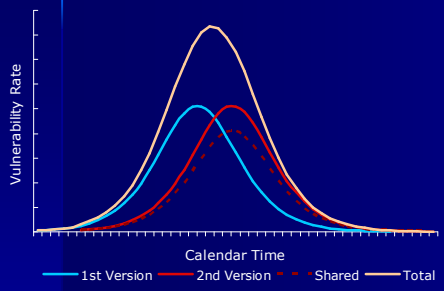
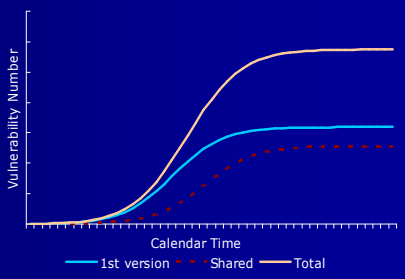
One-hump MVDM



<One-Hump MVDM Rate>



<One-Hump MVDM>

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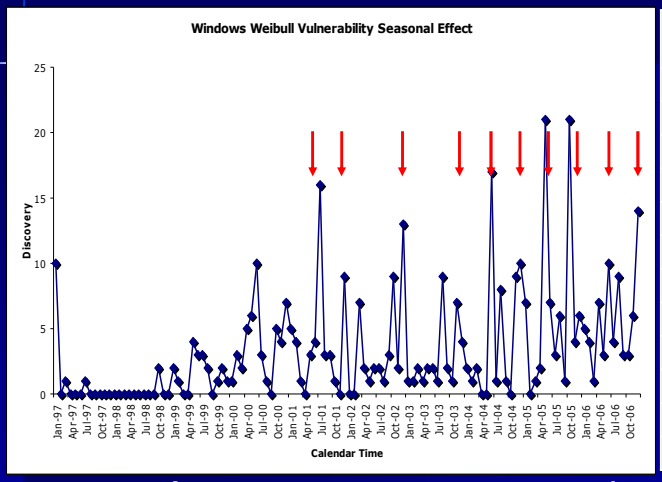
Seasonality of Vulnerabilities



Month	Seasonal Effect
March	-1.213
April	-1.846
May	1.123
June	1.888
July	0.008
August	-0.017
September	-2.226
October	1.141
November	-0.260
December	2.068
January	-1.059
February	-2.122

- ARIMA (AutoRegressive Integrated Moving Average)

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Recent Conference Papers

- W. S–W. , O. H. Alhazmi, and Yashwant K. Malaiya, *Assessing Vulnerabilities in Apache and IIS HTTP Servers*, Proc. of the 2nd IEEE International Symposium on Dependable Autonomic and Secure Computing Sept. 29-Oct. 1, 2006. pp.103-110.
- O. H. Alhazmi, W. S-W., and Yashwant K. Malaiya, *Security Vulnerability Categories in Major Software Systems*, Proc. of International Conference on Communication, Network and Information Security, Oct. 9-11, 2006. pp.138-143.
- J-Y. Kim, O. H. Alhazmi and Y. K. Malaiya, *Vulnerabilities in Browsers: Trends in Internet Explorer and Firefox*, Proc. of 17th IEEE International Symposium on Software Reliability Engineering, Nov. 7-10 2006.
- W. S-W., O. H. Alhazmi, and Y. K. Malaiya, *An Analysis of the Vulnerability Discovery Process in Web Browsers*, Proc. of the 10th International Conference on Software Engineering and Applications, Nov. 13-15, 2006

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