Leveraging Complexity in Software for Cybersecurity

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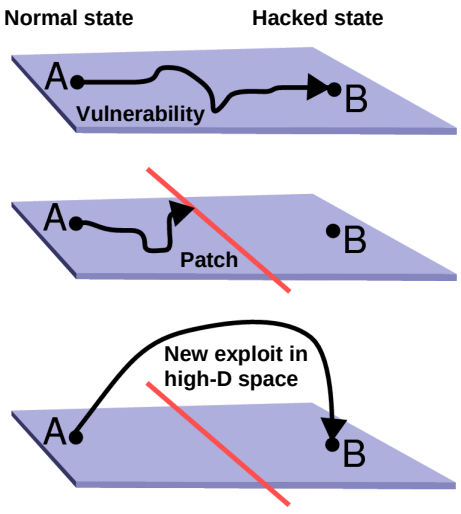
Combinatorial explosion generates fundamental asymmetry of cyber defense

- **Vast state space defies enumeration, even for desktop computers; new attacks every day**
- **Turing completeness makes behavior effectively unpredictable**
- **Numerous hidden attack vectors give attackers asymmetric advantage**
- **Current cyber defenses amount to one "Maginot Line" after another**



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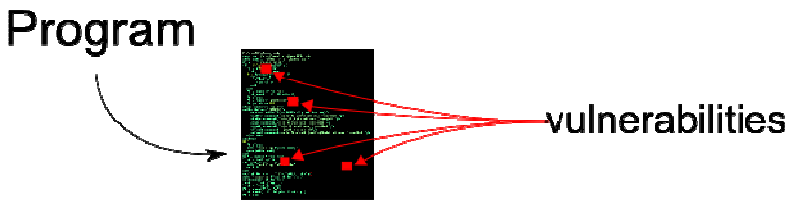
Securing an arbitrary code is not just hard; it's impossible

- **Restated: Generic code has vulnerabilities that are unprovable and unknowable**
  - – *Not* statistical, even in principle
  - – Turing completeness demands that a generic code is undecidable



- **So now what?**

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Complexity makes cyber threats *asymmetric*

- **Developer, user, *and attacker* all don't know where the vulnerabilities are (*undecidable*)**
- **Asymmetry: One vulnerability compromises the whole code**
  - – Developer has to find all of them (impossible in general)
- **No one can guarantee "this code is clean" or even quantify improvement**

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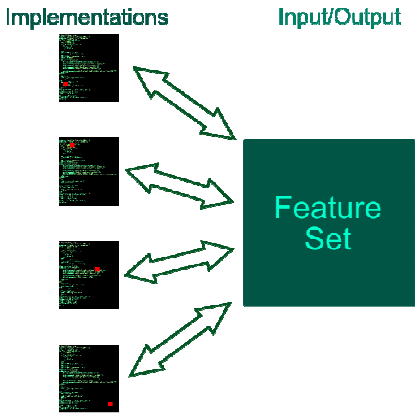
Observation #1: A program's feature set has many implementations



- **Feature set is defined by a test suite**
- **Test suite verifies that an implementation conforms to desired functionality**
- **Test suite is a sample; cannot realistically cover all possible input/outputs**
- **Vulnerabilities arise from untested input/outputs**
- **Any feature set has infinitely many implementations**
  - Finite large number if size is bounded

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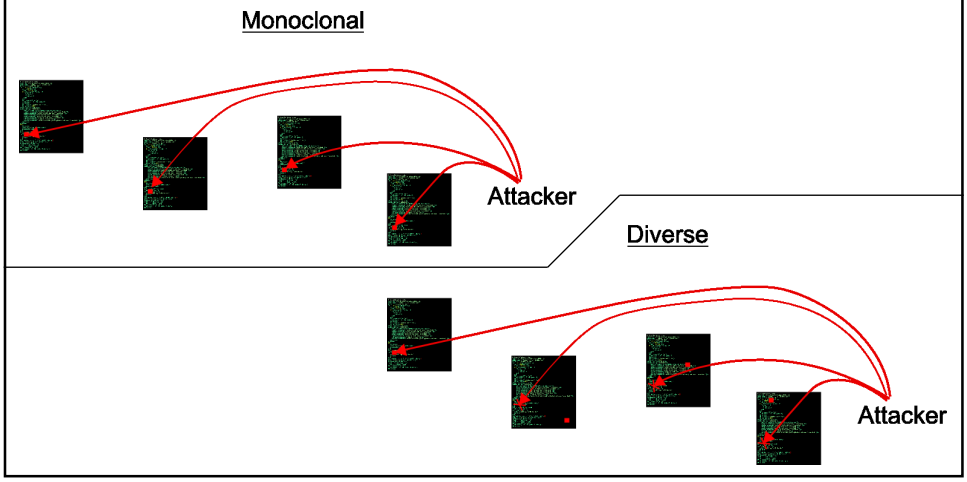
Observation #2: Ensemble of instances permits the formulation of statistics

- **Assume: Multiple implementations randomize security holes**
- **Ensemble of multiple-version, "randomized" undecidable codes allows formation of security *improvement* statistics**



High-reliability systems can be constructed from "*N*-version software"

- **Space Shuttle: 4 computers, identical software, different hardware components, same design**
  - Focus is on hardware faults
- **Similarly, software redundancy used mostly for control systems up to now**
  - *N*-version software: Multiple versions implemented to the same feature set by different developers
- **Models of *N*-version software view the control system as a stochastic process that walks the code graph of the software**
  - Control system takes the place of a "fuzzer"

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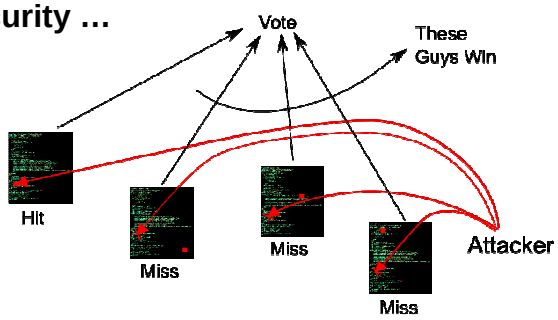
Similarly, *N*-version software can quantifiably improve cybersecurity

- **Clear generalization of *N*-version reliability to cybersecurity …**



- **… but there are important differences requiring enabling technology**
  - Compromised versions must be removed and replaced
  - Hand-made new versions are time-consuming and expensive
    - **May repeat previous mistakes**

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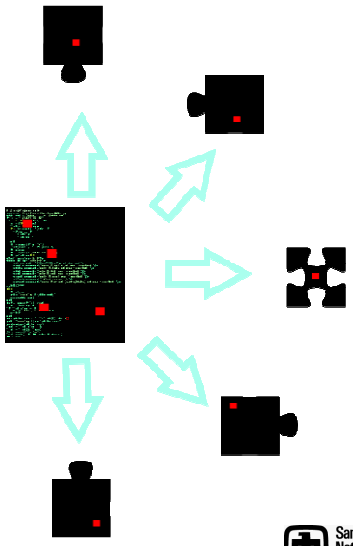
A simple example: Diverse software can be constructed from components

- **Component-based codes automatically conform to a feature set if the constituent components conform to their individual feature sets (semantic interfaces)**
  - Multiple implementations of the code amount to multiple versions of components
  - Components can be mixed and matched to form a combinatorial number of code implementations



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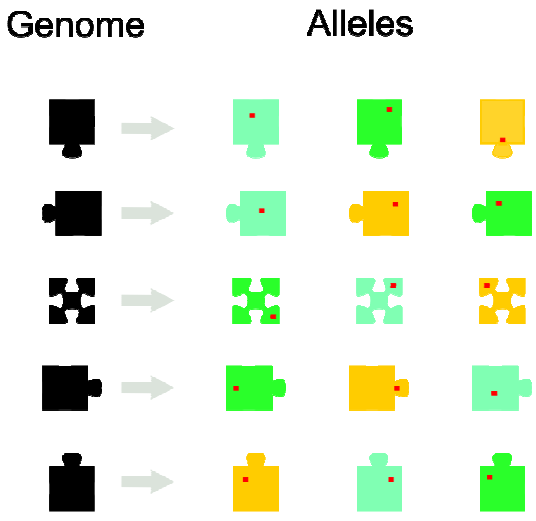
Living systems adapt to cope with unknowable attacks



- **A component type is similar to a gene; component implementations are similar to alleles of a gene**

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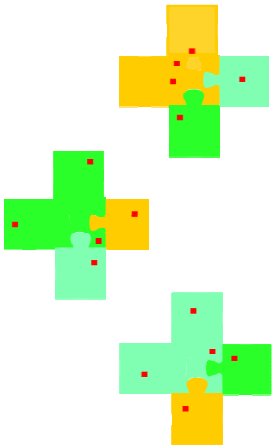
Reassemble alleles into individuals



- Different alleles can be assembled into new individuals that have “randomized” security holes
- New individuals are differently vulnerable and potentially adaptive

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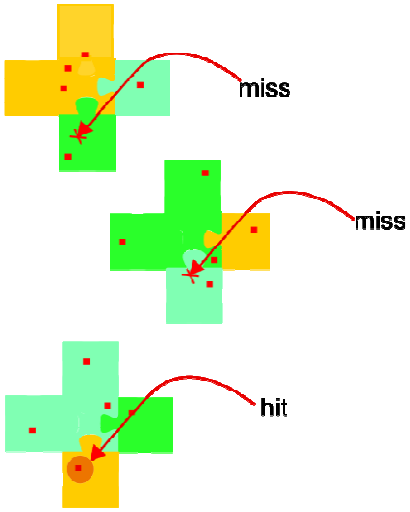
Compare responses from individuals



- Now different individuals will produce the same feature set but react differently to attacks

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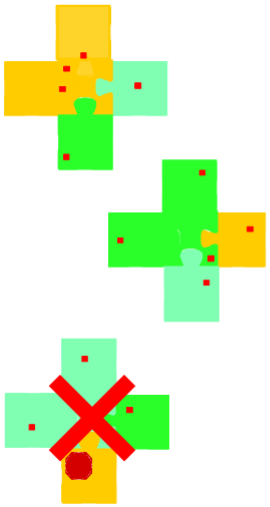
Evolve new and more robust individuals



- **Eliminate the one with the differentiated response**

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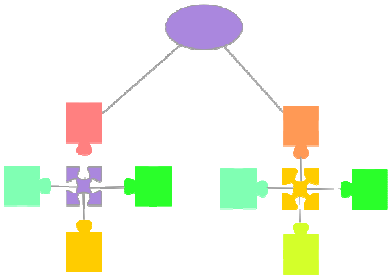
Genetic approach is a special case of fault-tolerant system design

- **Previous genetic approach is a contrived example of a network of entities robust to attack …**



- **… others certainly exist**
  - Seek more efficient examples that do not require total replication of every attackable system
  - Seek an arrangement of entities that has no single point of failure

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Research needs: Quantify and automate "program randomization"

- **Exploit existing compiler code-rewriting techniques**
  - Stack randomization, "semantically invariant" rewrites, etc.
  - Obfuscation techniques
- **Quantify, or at least *qualify*, sufficient randomness to expect that vulnerabilities do not repeat**
  - Use "fuzzers," emulation, and automated software analysis to find and compare *some* implementation-induced vulnerabilities
  - Use data to model the prevalence and rate of exposing new vulnerabilities
- **Automate the process of finding new versions**
  - Genetic programming techniques hold promise
    - **We are starting from a known implementation**
    - **Seeking only diversity**

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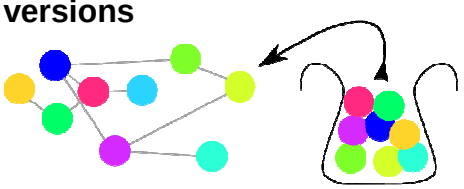
Research needs: Algorithms to exploit *N*-version concept for cybersecurity

- **Algorithms that implement the *N*-version idea but automatically remove compromised versions and create new ones**
  - Similar to biological selection process
  - Diversity over ensemble and over time
- **In-depth distributed redundancy and voting**
  - Decentralized methods to prevent single points of attack
- **Selecting entities from a previously generated collection to form software versions**
  - Starting from one or a few implementations, derive variants by "diffusing" code while maintaining feature set



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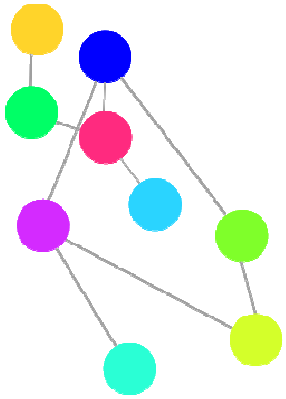
Generalization: Seek the emergent property of robustness to attack



- **Seek a generalized approach similar to RAID, where both diversity and voting are incorporated in-depth**
  - Eliminate the need for complete replication of diverse programs
  - Eliminate single points of failure
- **Seek a network of entities that are collectively robust to attacks "in the cloud"**
- **Entities can generalized to**
  - Programs
  - Hardware
  - Networks
  - Systems of these systems
  - And so on …

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Conclusion: Software complexity enables a new approach to cybersecurity

- **Complexity science helps cybersecurity confront the unknown and unknowable**
  - A single implementation is unknowable and unpredictable
  - Ensembles of unknowables provide potentially quantitative vulnerability measures
- **Practical systems will benefit from means for generating and measuring diversity**
  - Is there a "Hamming distance" for differing implementations?
- **Diversity is one way to turn complexity on the attacker**
  - Attacker cannot assume uniformity and permanence of target
    - **Vary over space (ensemble) and time (annealing)**
  - Redundancy offers a way to detect and recover from attacks

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