Verification Games: Making software verification fun

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Software engineering has been wildly successful

- Software pervades every aspect of our lives
  Try living a day without it!
- Software provides the value in our gadgets
- Huge economic impact
- Increasingly sophisticated functionality
  – We always want to do more!
Software engineering is challenging

Mathematics:
• Modeling
• Analysis

A non-ideal component: People!

Both aspects are intellectually deep
• New slide??
• SE has been a huge success – maybe the most of any computing field
• (or just say it!)

• SE encompasses technical and psychological/management [need better word!] boundaries
Hard problems in software engineering

- Choosing modularity and abstractions
- Task breakdown
- Dividing tasks between people and tools
- Transparent vs. powerful tools
- Optimizing intractable problems
- Cooperation, competition, and specialization
- The role of training
- Information overload
- Making SE fun
Angry Birds
Software verification

```
[mnote@monarch level]$ ant check-nullness
Searching for build.xml ...
Buildfile: /homes/gws/note/demo/java/Translation/build.xml

clean:
[delete] Deleting directory /homes/gws/note/demo/java/Translation/bin
check-nullness:
[mkdir] Created dir: /homes/gws/note/demo/java/Translation/bin
[jsr308.java] Compiling 14 source files to /homes/gws/note/demo/java/Translation/bin
[jsr308.java] javac 1.7.0-1src308-1.1.4
```
Which is more fun?

• Play games
• Prove your program correct
Crowd-sourced software verification

Goal: Verify software while you wait for the bus
• Make software verification easy and fun
• Make the game accessible to everyone
• Harness the power of the crowd
Programming is like a game

Fun puzzles that compel me to solve them:
• minimize a test case
• fix a bug
• create a feature
• refactor

When is it not fun?
What is usability in software engineering?
Pipe
Jam
game
demo
Highly-skilled, expensive labor

Free labor

Bug detected, notify programmer

Completed game with buzzsaws
Example: encryption

Goal: no cleartext is sent over the network

Pipe $\leftrightarrow$ a variable
Pipe width $\leftrightarrow$ narrow: encrypted, wide: cleartext
Ball $\leftrightarrow$ a value
Ball size $\leftrightarrow$ small: encrypted, large: cleartext
Pinch point $\leftrightarrow$ network communication
Unmodifiable pipe/ball $\leftrightarrow$ cleartext from user
**Example: null pointer errors**

Goal: no dereference of `null`

Pipe ↔ a variable
Pipe width ↔ narrow: non-null, wide: maybe null
Ball ↔ a value
Ball size ↔ small: non-null, large: null
Pinch point ↔ dereference
Unmodifiable pipe/ball ↔ literal `null`
Program ↔ game correspondence

Intuition: dataflow

Pipe ↔ a variable
Pipe width ↔ a property of the variable (type)
Ball ↔ a value
Ball size ↔ a property of the value
Pinch point ↔ requirement
Unmodifiable pipe/ball ↔ requirement
Type flow vs. dataflow

• Multiple flows per variable
  – A variable’s type may have multiple qualifiers
    `@Immutable Map<@English String, @NonNegative Integer>`

• Some variables are not represented at all
  – primitives (int, ...) when analyzing null pointer errors

• No loops
  – If program is verifiable, solvable in polynomial time
  – Human leverage: high-level pattern matching, placement of buzzsaws/casts

More accurate intuition: type constraints
  – Solving a game = type inference
  – Computers do a poor job
Other examples

- SQL injection
- unintended side effects
- format string and regexp validation
- incorrect equality checks
- race conditions and deadlocks
- units of measurement
- aliasing
- 27 of the CWE/SANS Top 41 Most Dangerous Software Errors
- ...

Type systems for verification

- Modular; local reasoning & understanding
- Equally powerful as any other verification technology (theorem proving, model checking, ...)

- Less effective for correctness of numerical computations
- Not good for full functional correctness
- Not good for temporal properties (focus on data)

How do these properties help/hinder the game?
3-way collaboration: machines, players, verification experts

1. **Machines**: Inference and optimizations
   - Brute force is not feasible for large programs
   - Error messages from type inference systems are poor

2. **Players** do work that automated tools cannot
   - Use intuition & pattern-matching to place cheats

3. **Verification experts** do work that players cannot
   - Classify un-verifiable code as safe or insecure
Machine optimization

• Simplify the challenge to its essence
  – Related to the program/problem duality

• Optimization techniques:
  – Abstract interpretation
  – Type inference & constraint propagation
  – Heuristic solving

• In Pipe Jam:
  – Remove multiple pinch points in a row
  – Remove pipes that suffer no conflicts
  – Set pipes to known values, forbid changes to them
**Elide irrelevant information**

- Example: primitives (int), when proving lack of null pointer errors

- Also loses documentation, program context!

- Leave in some easy challenges so players feel good about progress
Information overload & relevance

• Too much detail: player/user gets distracted
• Too little detail: unable to produce useful result

• Example: optimization
• Example: hiding details
Avoiding the big picture

Novice users accomplished more when given less information but given guidance [“Reducing the barriers to writing verified specifications”, Schiller & Ernst, OOPSLA 2012]
The gaming community

A potentially rich resource

– Angry Birds: 5 million hours of play time *per day*

– 200,000 cumulative years spent (as of 2011)

How do gaming and developer communities differ?
Collaboration and competition

Collaboration:
• Teams solve challenges
  – Team scoring
• Share solved levels, scripts
• Interaction: chats, forums, ...

Competition:
• Leaderboards, badges, challenges
Managing multiple solutions

• A player works on one level at a time
  – Score reflects effect on entire game world
  – Player can indicate need for changes on a different level
  – Player may accept a reduced score – avoid local maxima

• A player/team works in its own universe
  – Can save, restore, merge
  – Best solutions made available to other players
Demo: Traffic Jam
Problem decomposition

Program design methodologies:
• Procedural
• Object-oriented
• Functional
• Logic programming
• Design patterns

Lesson from software engineering:
• No one organization is best for all tasks
• Tradeoffs among competing desiderata
GridWorld

• Problem with Classic: action at a distance
  – Colored pipes are linked & have the same width
  – Represent different uses of the same variable
  – Game abstractions are same as the program’s
  – Goal: bring information together
Problem: action at a distance

Pipe colors indicate non-local dependences: uses of the same variable must be consistent.
Organizing a program’s constraints

• Programmer-supplied decomposition
  – Classes, methods
  – Programmer probably had a good reason
  – But: variables & calls cross-cut these structures

• Alternate decomposition:
  – Bring together variables, split apart method bodies
Demo: Flow Jam

Pipe

Jam
Just a new skin for the same game

• Pipes \(\rightarrow\) boxes
  – One box for arbitrarily many pipes of the same color
• Pipe connections \(\rightarrow\) lines
  – Didn’t eliminate action at a distance, but made it explicit

Identical constraints and XML input file
Player is solving the same problem, but it feels like a different game
We plan A/B testing
Implications of Grid World’s variable-oriented layout

• Fewer boards, but bigger ones
  – Lots of explicit links
  – Layout and navigation are more challenging

• More compact representation
  – No traveling balls/cars, no sub-boards
  – See more on the screen

• Two game-playing modalities: conflicts, layout
Type inference is challenging

- Example: prove that `myMap.get(someKey)` returns a non-null value
  (recall: `Map.get` returns null if the key isn’t in the map)
  - `myMap` is declared as `Map<KeyType, @NonNull valueType>`
  - `someKey` is a key in `myMap`

- Example: polymorphism (Java generics)
Design goals for a (software engineering) game

• Address a hard problem
• Connect players to the real work they are doing
• Scale to (and be useful for) real problems

• Fun
• Use human skills
• Minimal distractions from underlying problem

• Allow and encourage collaboration
Designing a program analysis

(Examples: model checking, abstract interpretation)

Key problem: the abstraction

• Capture the essence of the problem
• Too much detail: infeasible analysis
• Too little detail: does not prove desired properties

Designer insight and iteration are crucial
Each new successful abstraction is a breakthrough
Designing a machine learner

Key issues:
• Learning algorithm (SVM, decision tree, neural network, genetic algorithm, ...)
• Feature space (problem representation): the information fed to the algorithm

State of the art:
• Try lots of algorithms
• Try lots of feature spaces
• When one works, publish it
Designing a (software engineering) game

Goals:
• Address a hard problem
• Use human skills
• Fun

A challenging task with no simple rules
Modularity and abstraction make it even harder
Some successful games
ESP game (image labeling)

What do you see?

- taboo words: peace, lay
- guesses: sheeps..., sheep

Score: 100
Time: 2:21
Duolingo (translation)
The Norwich line steamboat train, from New-London for Boston, this morning ran off the track seven miles north of New-London.
Image segmentation

(a) Color Labels (ACA)  (b) Texture Classes

(c) Crude Segmentation  (d) Final Segmentation
FoldIt (proteomics)
FoldIt

- Proteomics game at UW
- Effectively created the genre of games that solve hard problems
- Three Nature papers in under 2 years
- Over 240,000 players, 200+ new per day
## Comparison of games

<table>
<thead>
<tr>
<th>Game</th>
<th>Abstraction?</th>
<th>Modularity?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image labeling</td>
<td>✗</td>
<td>✓</td>
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<td>Translation</td>
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<td>OCR</td>
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<td>Image segmentation</td>
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<tr>
<td>Protein folding</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Type inference</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Challenge: create more games that are abstract and modular
Abstraction and modularity in game design

Abstraction
• Is the player doing the goal task directly?
• In an abstracted game:
  – No need for expertise in the problem domain
  – No obvious connection to the real-world value

Modularity
• Each player solves part of the overall problem
• The system combines the contributions of different players
• Programs have natural modularity, created by the programmer
  In Pipe Jam:
  – World = program
  – Level = class
  – Board = method
Pipe Jam solves multiple problems

Anything that can be expressed as a type system:
• null pointer errors
• encryption
• SQL injection
• unintended side effects
• format string and regexp validation
• incorrect equality checks
• race conditions and deadlocks
• units of measurement

For a new type system:
• Map type system into the Pipe Jam schema
• Convert a program to a game instance
Pipe Jam also contains a layout game (different skill set)
One game to rule them all?

Problem reduction:
Many problems can be converted to SAT

\[(A \lor B) \land (\neg A \lor \neg B \lor \neg C) \land (\neg A \lor B \lor C)\]

Can we gamify all those problems simultaneously?
Don’t think about SAT

... when you play the game

... when you design the game

Translation to SAT:

• Explodes problem size
• Destroys problem structure, no human intuition
Casual gamers vs. trained experts

With time, players develop unique skills
• A plumber might be a protein-folding savant

Our focus is not on casual gamers
Useful work comes from trained expert players
Human advantage

Do people outperform verification algorithms?

Inference is undecidable (human experts $\gg$ algorithms)

**Hypothesis:** no for correct, verifiable programs,
yes for incorrect or unverifiable programs

**Location of buzzsaws** is key to the whole approach

Game players only have to **reduce** overall verification cost, not fully verify the program
Player performs optimization

- Type error (Jam): -75 (or -1000)
- Wide inputs or narrow outputs: +25 (or +10)
- Constant offset to make positive

\[
\max_{A} \alpha \sum_{c \in C} \text{satisfied}(c, A) + \sum_{a \in A} \beta_a \text{desired}(a) + \gamma
\]
Scoring

Score is influenced by:
• Collisions (verifiability)
• Use of buzzsaws (trusted assumptions)
• Pipe widths, distinguishing input and output pipes (re-usability of modules)

Multiple solutions may be possible

Score is a proxy for quality of verification result
• Have we just rephrased the hardest question?
• Heuristics & search strategies for an optimization problem
• Discover algorithms that may outperform players
Other games being built

• Invariant detection (a la Daikon)
• Model checking
• Model merging
• Register allocation
• ... your ideas here!

* These are not my ideas; many come from DARPA’s Crowd-Sourced Formal Verification Program (Dr. Drew Dean, PM)
Play now at Verigames.com
Creating test cases

• Given a solved game, seek input balls that cause a conflict
• This can be converted to a test case

Other games being built:
• Model checking
• Model merging
• Register allocation
Pipe Jam status

• Prototype exists
  – Tested on modest programs (~100,000 lines)
  – Players say it is “kind of fun”

• Many challenges remain
  – Create tests (example failures, or counterexamples)
  – Scale to multiple players (parallelism, social aspects)
  – Make the game more fun
Gamification of SE (program verification)

Goal: cheaper verification $\Rightarrow$ more verification

Pipe Jam and Flow Jam games...
- encodes correctness condition
- utilizes physical intuition & human insight
- is playable by anyone

Play at http://verigames.com
Credits

Collaborators on Verification Games project:
Funding: DARPA
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- The role of training
- Information overload
- Making software engineering fun

Games↔SE: A useful, if imperfect, analogy
Science benefits from:
- A games perspective on SE
- A SE perspective on games
May apply elsewhere
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