ScottCheck: An Adventure in Symbolic Execution

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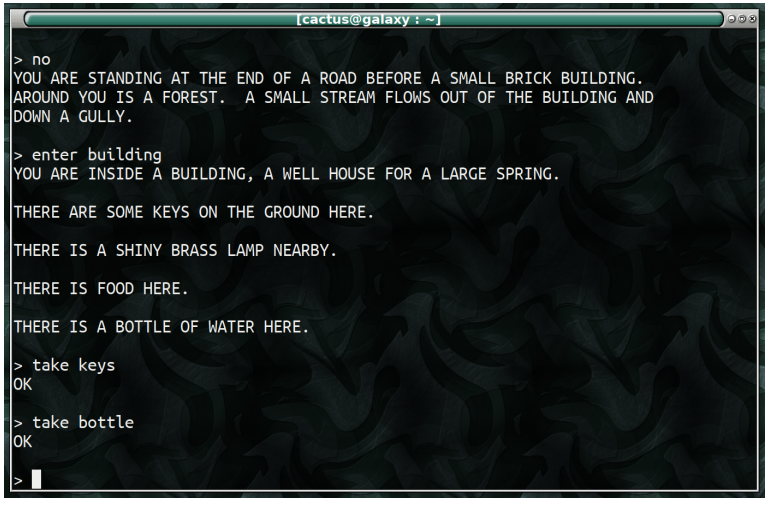
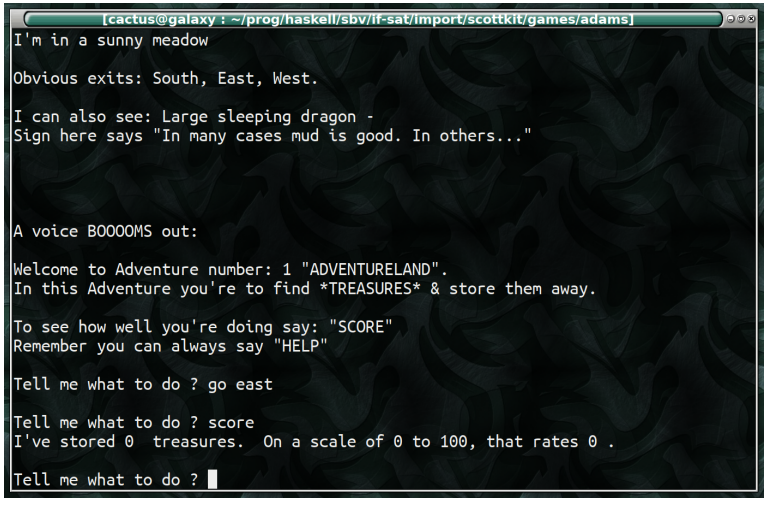
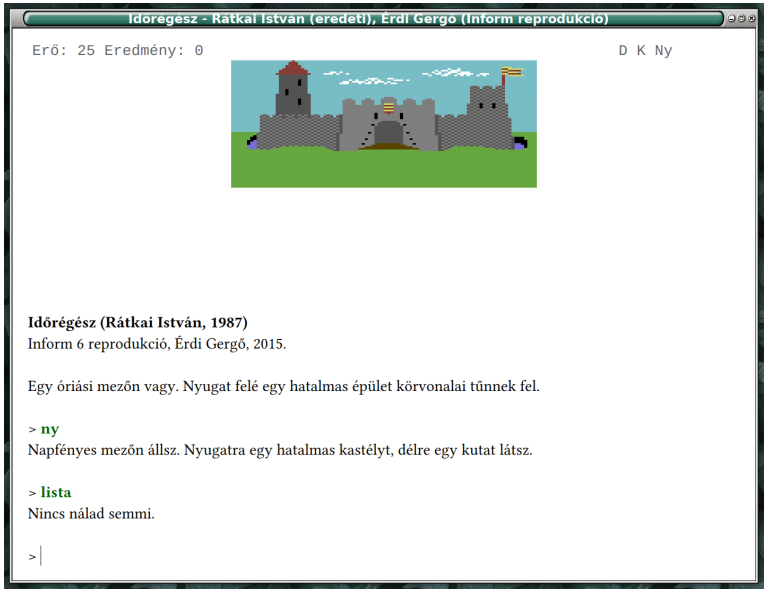
1. Structure and Interpretation of Adventure Games

Text adventure games







Text adventure games

- Interactive fiction
- Text adventure games
  - Subset of interactive fiction: well-defined **win state**
  - (Debian 2.0 installer in 1998?)
  - Unwinnable games are faulty
- Under the hood
  - Game data + interpreter
  - *Infocom*, *ADS*, *Inform*, ...
  - *Adventure International*

Adventure International

- Scott Adams (unrelated to the Dilbert guy)
- Late '70s home computers
- Goal: move all items marked as *treasure* to the single location marked as the *treasury*
- `SCORE` command shows number of treasure collected. Win by issuing `SCORE` with max score.
- Game data: text file containing magic numbers and string literals

Example data file: Header

```
0
6           -- Number of items
10          -- Number of script lines
18          -- Dictionary size
5           -- Number of rooms
-1          -- Player carry capacity
3           -- Starting room
1           -- Max score
3           -- Word length
-1          -- Lamp capacity
7           -- Number of messages
1           -- Treasury room number
```

Example data file: Dictionary

```
"AUT"  "ANY"
"GO"   "NOR"
"SCO"  "SOU"
"INV"  "EAS"
"LOO"  "WES"
"OPE"  "UP"
""     "DOW"
""     "DOO"
""     "KEY"
""     "CRO"
"GET"  "COI"
""     ""
""     ""
""     ""
""     ""
""     ""
""     ""
""     ""
"DRO"  ""
```

Example data file: Rooms & messages

```
0 0 0 0 0 0 ""
0 2 0 0 0 0 "gorgeously decorated throne room"
1 0 3 0 0 0 "square chamber"
5 0 0 2 0 0 "gloomy dungeon"
3 0 0 0 0 0 "dungeon cell"
0 3 0 0 0 0 "damp, dismal crypt"

""
"I smell something rotting to the north."
"It's locked."
"OK"
"Vampire cowers away from the cross!"
"Vampire looks hungrily at me."
"Vampire bites me!  I'm dead!"
"I'm not going anywhere near that vampire!"
```

Example data file: Items

```
"Sign says: leave treasure here, then say SCORE" 1
"Wooden cross/CRO/" 2
"Locked door" 3
"Brass key/KEY/" 5
"Open door leads south" 0
"*Gold coin*/COI/" 4
"Vampire" 5
```

Example data file: Script

```
300 0 0 0 0 0 9750 0
450 0 0 0 0 0 9900 0
600 0 0 0 0 0 9600 0
25 64 0 0 0 0 150 0
757 42 72 0 0 0 300 0
757 42 40 80 0 0 10803 9600
157 82 80 0 0 0 8164 0
100 122 21 0 0 0 600 0
100 122 26 0 0 0 750 0
25 122 26 0 0 0 963 0
1508 122 26 0 0 0 1050 0
```

Example data file: Script

```
757 42 72 0 0 0 300 0
```

- User input: `OPE DOO`
- Condition: Item 2 `"Locked door"` in current room
- Condition: Item 3 `"Brass key"` not available
- Action: Print message 2 `"It's locked"`

The Grand Plan

- Martin Lester's talk at WPTE 2020:
  - *ScottFree*: Off-the-shelf game interpreter written in C
  - Manually "partially evaluated" for a given game, infinite loops replaced with bounded ones, passed to *CBMC*
  - *CBMC* output passed to an SMT solver
- My approach: bubblegum and duct tape
  - Idiomatic Haskell interpreter
  - Changed just so, to use symbolic values
  - In one week

2. Monad Transformers for Concrete Interpreters

Interactive interpreter

- Parse game data into algebraic datatype `GameData`
- Game state

```
data St = St
    { currentRoom    :: Int16
    , itemLocations  :: Array Int16 Int16
    }
```

- Stack of monad transformers:

```
type Engine =
    ReaderT GameData (WriterT [String] (State St))

step :: (Int16, Int16) -> Engine (Maybe Bool)
```

(Return value: win/fail state)

- Thin layer of IO: get input, parse with dictionary, print output

3. Reducability Among Fictional Problems

Satisfiability

- *SAT*: Boolean satisfiability problem
  - Given a Boolean formula with variables, is it satisfiable?
  - Trivially in NP: we can verify a given var assignment by eval
  - But also NP-hard!
  - 3-SAT (CNF SAT with ≤ 3 literals per clause): the OG NP-complete problem
- Mature solvers chock full of heuristics
- *SMT*: Satisfiability modulo theories (e.g. integer arithmetic)
- Represent full game logic as a boolean formula with user input as the variables

4. Symbolic Execution and Puzzle Testing

Symbolic execution

- What is the value of

```
if x + (if b then 0 else 2) > x + 1 then 3 else 4
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if (if $b then $x + 0 > $x + 1 else $x + 2 > $x + 1)
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if (if $b then $x + 0 > $x + 1 else $x + 2 > $x + 1)
  then 3 else 4

if (if $b then False else True) then 3 else 4

if $b then 4 else 3
```

5. Notions of Adventuring and Monads

SBV-based interpreter

- Change representation of `St`:

```
data St = St
    { currentRoom    :: SInt16
    , itemLocations  :: Array Int16 SInt16
    } deriving (Generic, Mergeable)
```

- Structure of items is static!
- Follow type errors
  - `Num` operations Just Work™, Boolean operations need *SBV*-specific versions
  - `Mergeable` instances for MTL monad transformers
- `if_then_else` using rebindable syntax!

```
ifThenElse :: (Mergeable a) => SBool -> a -> a -> a
ifThenElse = ite
```

SBV-based interpreter: Combinators

- `Mergeable`-based versions of monadic combinators

```
sWhen :: (Monad m, Mergeable (m ())) =>
    SBool -> m () -> m ()
sWhen b act = if b then act else return ()
```

- Pattern matching on script code symbolically

```
sCase
    :: (Mergeable a)
    => SInt16
    -> [(Int16, a)] -> a -> a
sCase x cases def = go cases
  where
    go [] = def
    go ((k,v):kvs) =
        if x .== literal k then v else go kvs
```

Turning the crank

```
step :: (SInt16, SInt16) -> Engine (SMaybe Bool)
```

- *SBV*'s `Query` monad allows incremental SMT queries
- We keep running `step` with new inputs, until it can be satisfied
- Satisfying input recovered from SMT solver's state

```
loopState
    :: (SymVal i)
    => Query (SBV i)
    -> s
    -> (SBV i -> State s SBool)
    -> Query [i]
```

Recovering interactive mode

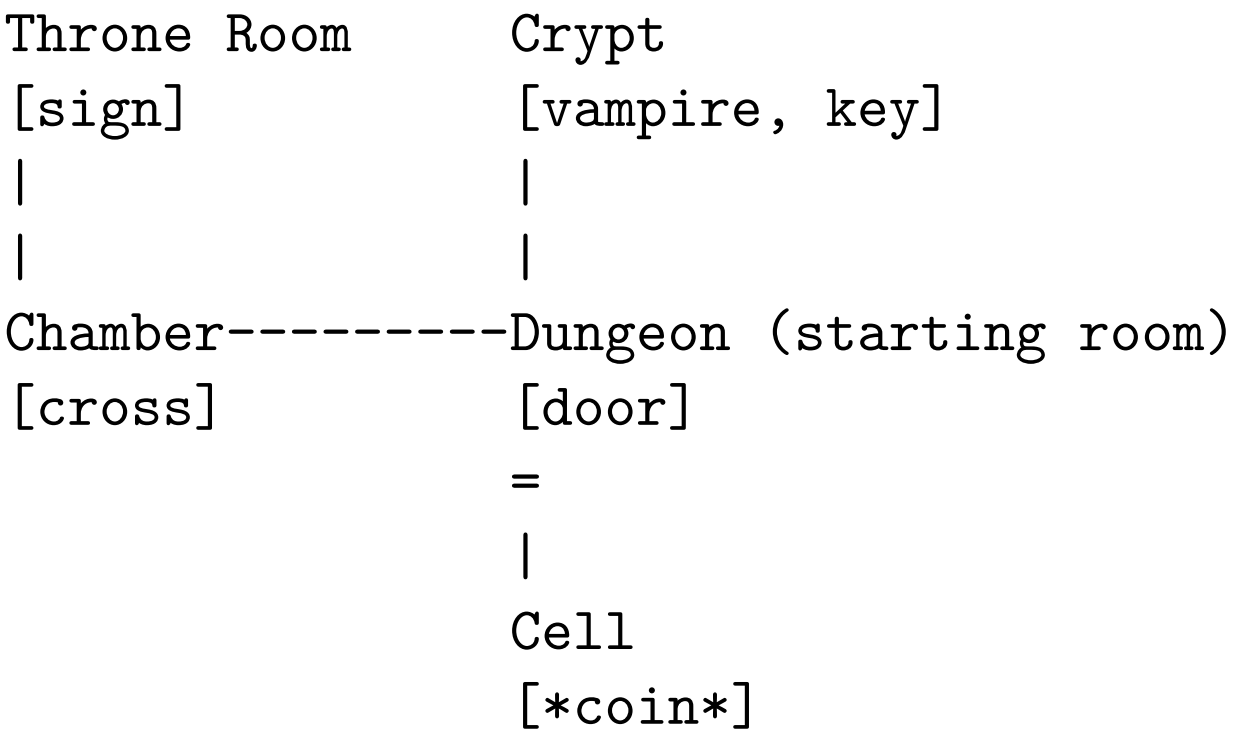
- The only source of "really symbolic" values is the input to `step`
- Idea: feed interactive input as single possible value, this ensures output has a single possible value as well

Recovering interactive mode

- The only source of "really symbolic" values is the input to `step`
- Idea: feed interactive input as single possible value, this ensures output has a single possible value as well
- Same interpreter can be used for checking and interactive execution!

6. Demo: *Here's one I made earlier*

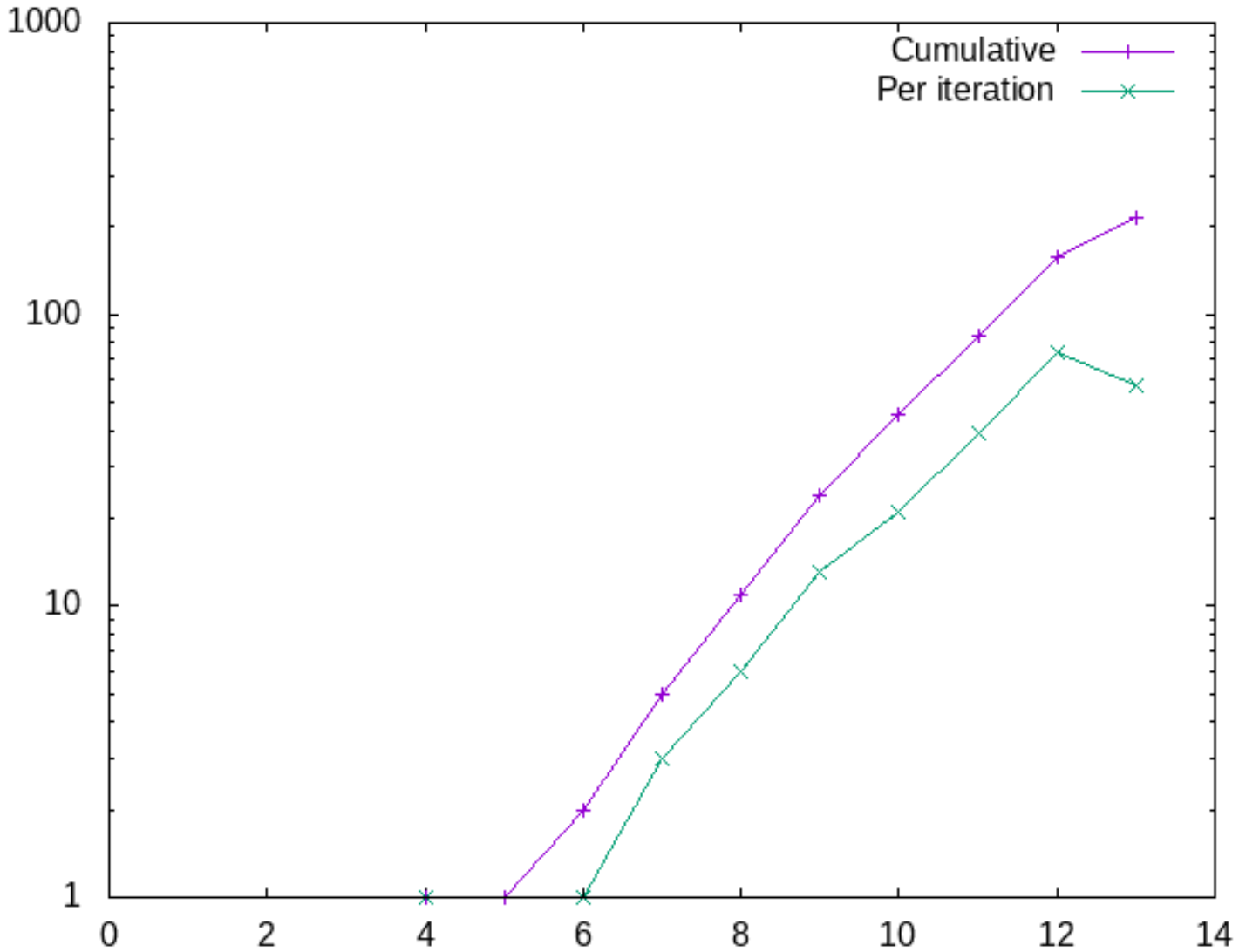
Demo: *ScottKit*, tutorial #4



Demo: *ScottKit*, tutorial #4

```
00:00 Searching at depth: 1
...
02:38 Searching at depth: 14
03:35 Solution found:
03:35    1. GO WEST
03:35    2. GET CROSS
03:35    3. GO EAST
03:35    4. GO NORTH
03:35    5. GET KEY
03:35    6. GO SOUTH
03:35    7. OPEN DOOR
03:35    8. GO DOOR
03:35    9. GET COIN
03:35   10. GO NORTH
03:35   11. GO WEST
03:35   12. GO NORTH
03:35   13. DROP COIN
03:35   14. SCORE
```

Demo: *ScottKit*, tutorial #4



(check-sat)

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Special thanks to Levent Erkök for helping out with SBV.

Questions?