Formal Verification of Computer Narratives

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Outline

1. Introduction
2. Interesting Temporal Properties
3. Representation
4. Verification
5. Conclusions and Future Work

Motivation

Narrative verification?

- Modern computer games typically have some kind of narrative backbone.
- Unfortunately, plot holes, non-sequiturs, and dead ends abound in the narratives of even *massively commercial* games.
- It would be nice to prevent against these.

Who cares?

- Game designers that want certain narrative properties.
- Large numbers of "playtesters" that try to find bugs by hand.
- Players that want information about the current game state.
- Computer scientists, who like solving problems.

Motivation

What can we do?

- Identify some interesting temporal properties.
- Represent computer narratives as finite state machines.
- Generate models and check properties automatically.

Computer Narratives

```
> look
It's pitch black, and you can't see a thing!

> inventory
You are carrying:
  a lamp

> light lamp
The lamp flickers to life.

> look
You're in a musty old cellar.  Prakash is here.
```

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Reachability

Reachability: is there a path from s to t?

- Binary yes/no: check $\mathcal{M}, s \models \mathrm{EF}\, t$
- Actual path: counterexample produced by checking $\mathcal{M}, s \models \neg \mathrm{EF}\, t$

Some interesting reachability questions:

- Can I lose? $\mathcal{M}, s_{current} \models \mathrm{EF}\, lose$
- How do I win? $\mathcal{M}, s_{current} \models \neg \mathrm{EF}\, win$
- How do I unlock this door? $\mathcal{M}, s_{current} \models \neg \mathrm{EF}\, door.unlocked$
- Are there any zombie states: $\mathcal{M}, s_{initial} \models \neg \mathrm{AG}(\mathrm{EF}\, win \vee \mathrm{EF}\, lose)$

Distance (δ)

Distance: shortest path from s to t

- $\delta(s,t) = \min\{n | \exists s_0, \ldots, s_n . s = s_0, t = s_n, s_i \rightarrow s_{i+1} \text{ for } 0 \leq i < n\}$

But $\delta(s,t)$ is just length of reachability counterexample produced by $\mathcal{M}, s \models \neg \mathrm{EF}\, t$, since BFS is used.

Separation (γ)

Separation: longest acyclic path from s to t

- $\gamma(s,t) = \max\{n | \exists s_0, \ldots, s_n . s = s_0, t = s_n, (s_i \rightarrow s_{i+1} \wedge (s_i \neq s_j \text{ for } 0 \leq j < i) \wedge (s_i \neq s_k \text{ for } i < k \leq n)) \text{ for } 0 \leq i < n\}$

Not obvious how $\gamma(s,t)$ can be efficiently checked in general.

Reoccurrence Radius (ρ)

Reoccurrence radius: longest path from s to any other reachable state t

- $\rho(s) = \max\{\gamma(s,t) | t \in S \wedge \mathcal{M}, s \models \mathrm{EF}t\}$

Can also compute $\rho(s)$ by finding a minimal r that makes the following formula valid:

- $\forall s_0, \ldots, s_{r+1}.((s_0 = s_{initial}) \wedge (s_i \rightarrow s_{i+1}$ for $0 \leq i \leq r)) \Rightarrow \exists i \exists j.(0 \leq i < j \leq r+1) \wedge (s_i = s_j)$

Intuition: find the shortest path length such that extending it any further will *always* create a cycle; this is the longest acyclic path length.

This is a propositional formula, and can be checked by SAT.

Pointlessness

A game is pointless: $\mathcal{M}, s_{current} \models \neg \mathrm{EF}\, win$
A game is p-pointless: it takes a maximum of p steps from pointlessness to actually losing.

How to calculate p?

- $p = \gamma(s_{pointless}, lose)$

If $\mathcal{M}, s_{pointless} \models \neg \mathrm{AG}(\mathrm{EF}\, lose)$, then $p = \infty$.
Otherwise, $p = \rho(s_{pointless})$.

Why? *lose* is a sink node, and reachable on all paths, so any putative acyclic longest path not including *lose* can be extended to include *lose*.

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Petri Nets

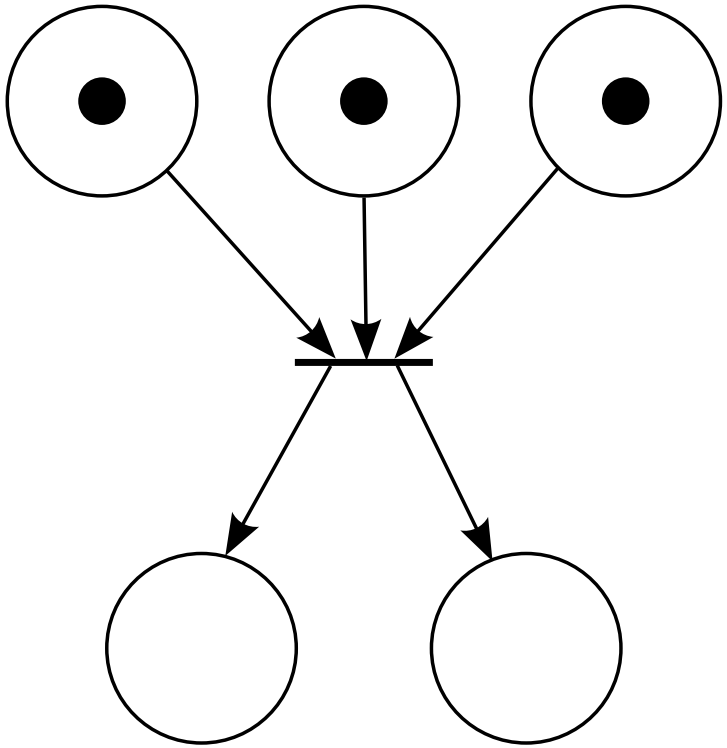
Represent computer narratives using Petri Nets.

- Compact encoding of large state space.

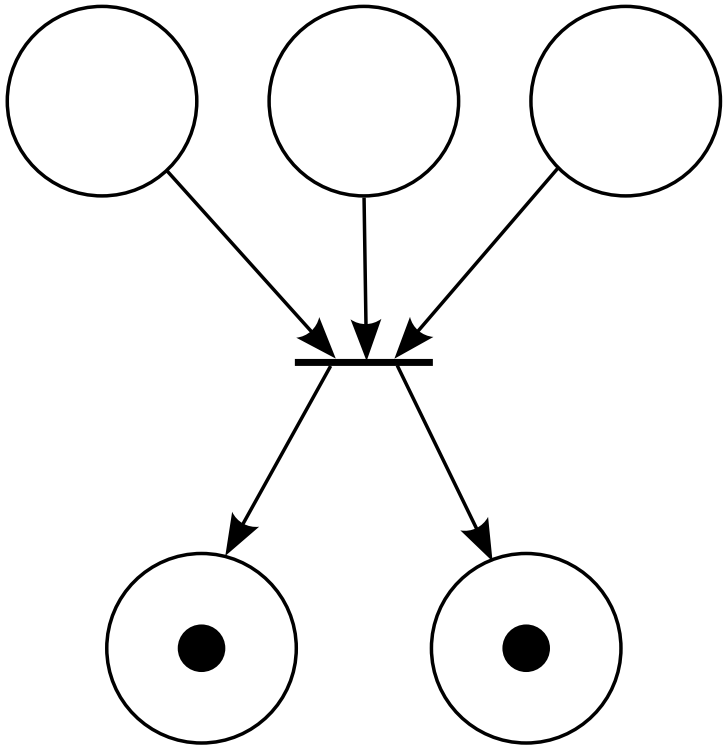
Consider "1-safe" Petri Nets:

- S, a set of *places*
- T, a set of *transitions*
- $F \subseteq (SxT) \cup (TxS)$, a *flow relation*
  - No arc connects two places or two transitions
- $M_0 : S \rightarrow \{0, 1\}$, an initial *marking*, or distribution of *tokens* over $s \in S$.
  - A 1-safe Petri Net has only 0 or 1 tokens in any place.
  - Markings are equivalent to states.
- A transition is *enabled* if all source places contain tokens.
- An enabled transition can *fire*, removing tokens from all source places and filling all destination places.

Petri Nets



Petri Nets



Narrative Flow Graphs

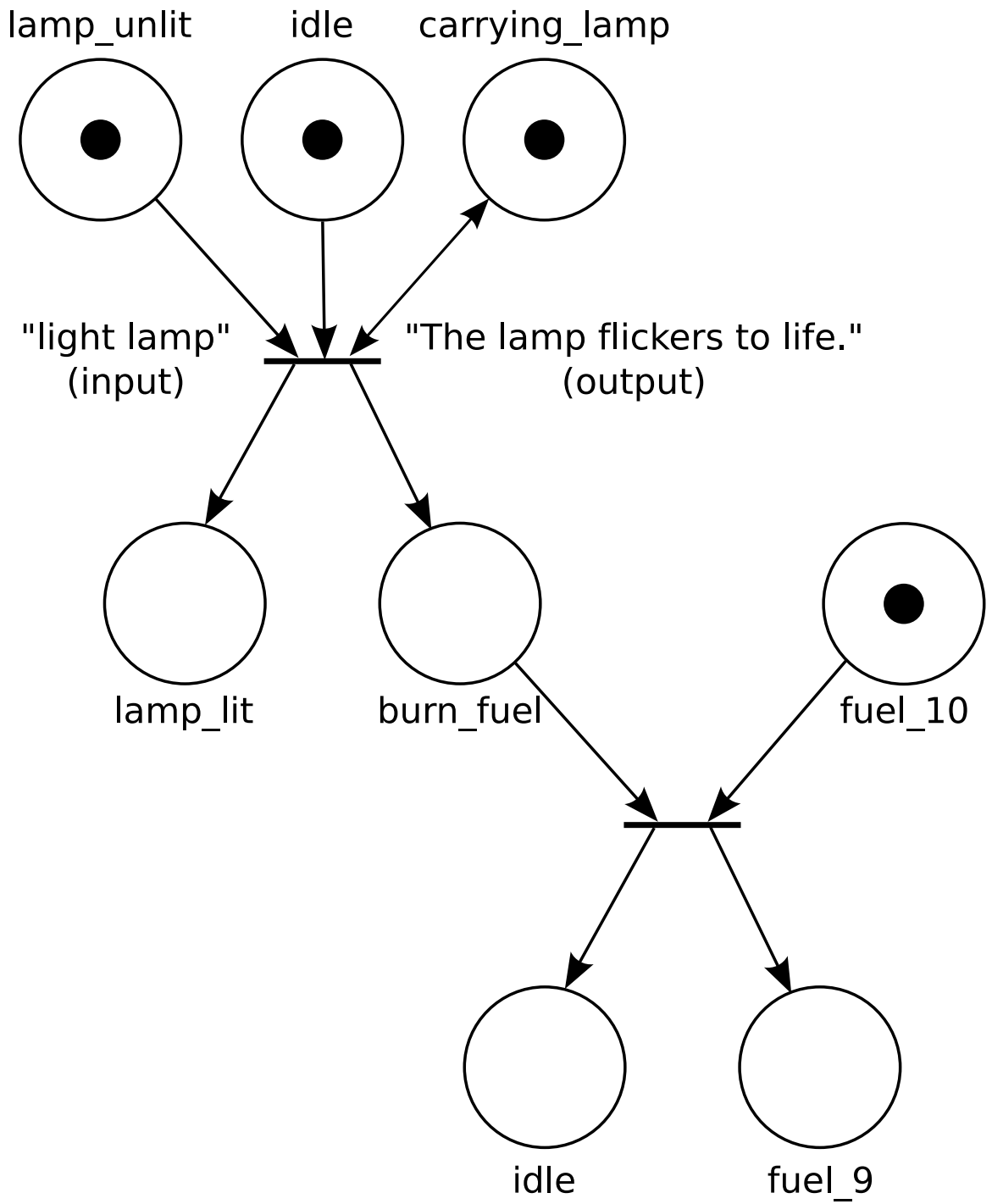
We extend 1-safe Petri Nets to *Narrative Flow Graphs* (NFGs).
Need some additional elements:

- M_{win}, a sink marking that signifies winning
- M_{lose}, a sink marking that signifies losing
- L, a set of labels
- $I : T \rightarrow L$, a mapping of transitions to input labels
- $O : T \rightarrow L$, a mapping of transitions to output labels
- $T_{actions} : t \in T \ . \ I(t) \in L$, action transitions
- $T_{internal} : t \in T \ . \ \neg(I(t) \in L)$, internal transitions

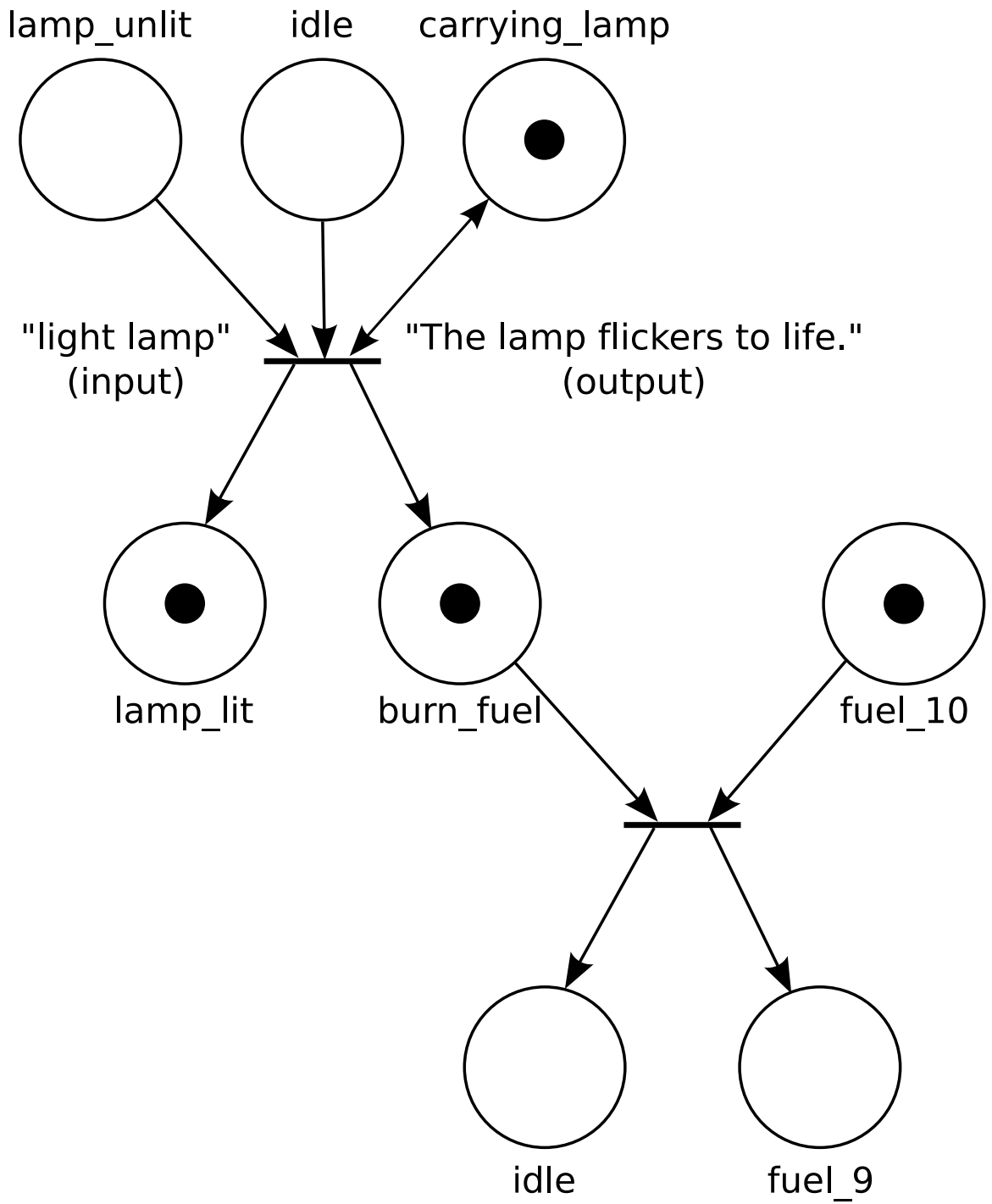
The narrative flows from M_0 to M_{win} or M_{lose} via some series of $t_a \in T_{actions}$ and $t_i \in T_{internal}$.

Internal transitions take priority, and firing is sequential.

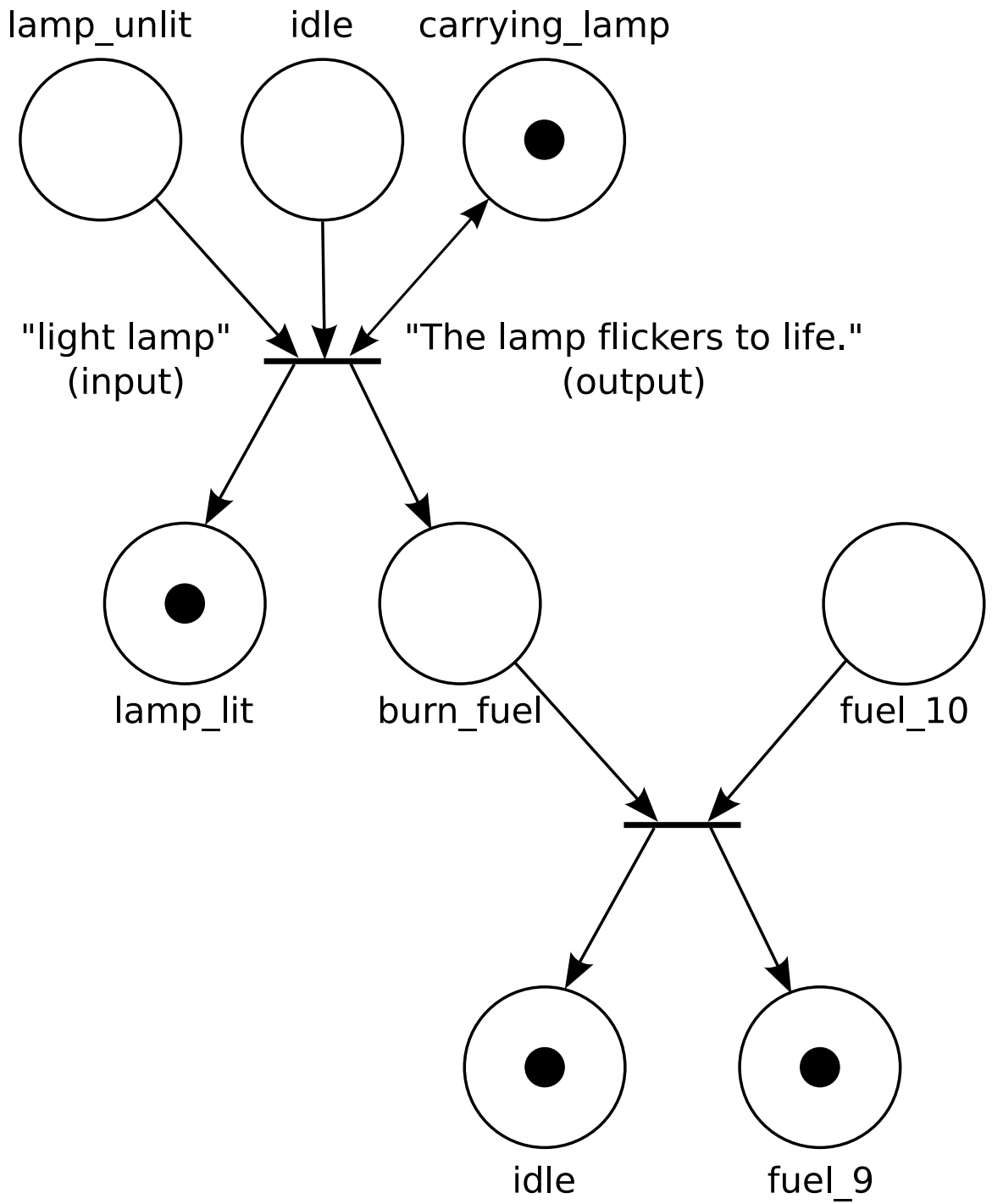
Narrative Flow Graphs



Narrative Flow Graphs



Narrative Flow Graphs



NFG Execution

```
initialize NFG
while (!won && !lost)
    while (some t_i ∈ T_internal enabled)
        fire t_i
    wait for user input
    switch (input)
        case "query win":
            M, s_current ⊨ ¬EF win
        case "query lose":
            M, s_current ⊨ ¬EF lose
        case "query moves":
            print l(t_a) for each enabled t_a ∈ T_actions
        case (l(t_a) for some enabled t_a ∈ T_actions):
            fire t_a
        default:
            "Sorry, try something else."
```

Programmable Narrative Flow Graphs

- Writing NFGs directly is painful and error-prone.
- The *Programmable Narrative Flow Graph* (PNFG) language and compiler attempts to alleviate this concern.
- Programmer writes narrative in imperative language.
- Compiler generates NFG for interpretation and verification.

Programmable Narrative Flow Graphs

```
object lamp {
    state { lit }
    counter { fuel 0 10 }
}

room cellar {
    (you, look) {
        if (you contains lamp && lamp.lit) {
            "You're in a musty old cellar.";
            lamp.fuel--;
        } else {
            "It's pitch black, and you can't see a thing!";
        }
    }
    ...
}
```

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Generating NuSMV Models

- For now, focus on simple reachability of win and lose.
  - `SPEC !EF win = 1`
- Translation from Petri Net (NFG) model is straightforward
- High sensitivity to variable ordering:
  - Might quickly run out of memory
  - Might spend hours and not make any progress
  - Might produce a solution in a few minutes
- Player can query paths to win and lose at any point.

Exploiting PNFG Structure

Efficient encodings of Petri Nets in NuSMV is critical.

- Exploit structure of code generated by PNFG compiler

Instead of modelling individual PN places, model tokens instead.

- Split net into disjoint S_{mutex}, each with only 1 token.
- Modelling by places: $|S_{mutex}|$ booleans per token.
- Modelling by tokens: $\lceil \log_2 |S_{mutex}| \rceil$ booleans per token.

Exploiting PNFG Structure

Three main applications:

1. Objects can only be in 1 room at a time. Cost per object is $\lceil \log_2 |R| \rceil$, where R is the set of rooms.
2. Scalars can only assume 1 value at a time. Cost per scalar is $\lceil \log_2 |C| \rceil$, where C is the set of unary counter values.
3. Program control can only be in 1 state at a time. Cost of `pc` is $\lceil \log_2 |P| \rceil$, where P is the number of nodes in CFG.

Experimental Results

narrative title	Cloak of Darkness	Cloak of Darkness	Return to Zork Ch. 1	Return to Zork Ch. 2	The Count
source	.nfg	.pnfg	.pnfg	.pnfg	.pnfg
rooms	3	4	10	21	22
objects	3	1	19	36	29
places	69	303	1275	1876	15378
transitions	167	462	3341	8030	82371
booleans	69	27	98	117	212
verifiable	yes	yes	no	no	no
steps to win	6	6	6	22	180

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Conclusions

- There are several interesting temporal properties in computer narratives.
- Petri Nets can represent large systems efficiently, and are suitable for modelling these narratives.
- Software verification is hard; exploiting structure in a high-level language can help.

Future Work

- Improve NuSMV model generation, see if we can compute reachability for larger problem sizes.
- Extend PNFG compiler to accept LTL and CTL specifications.
- Check other properties besides reachability, such as degree of pointlessness.