Testing Planning Domains (without Model Checkers)

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Overview

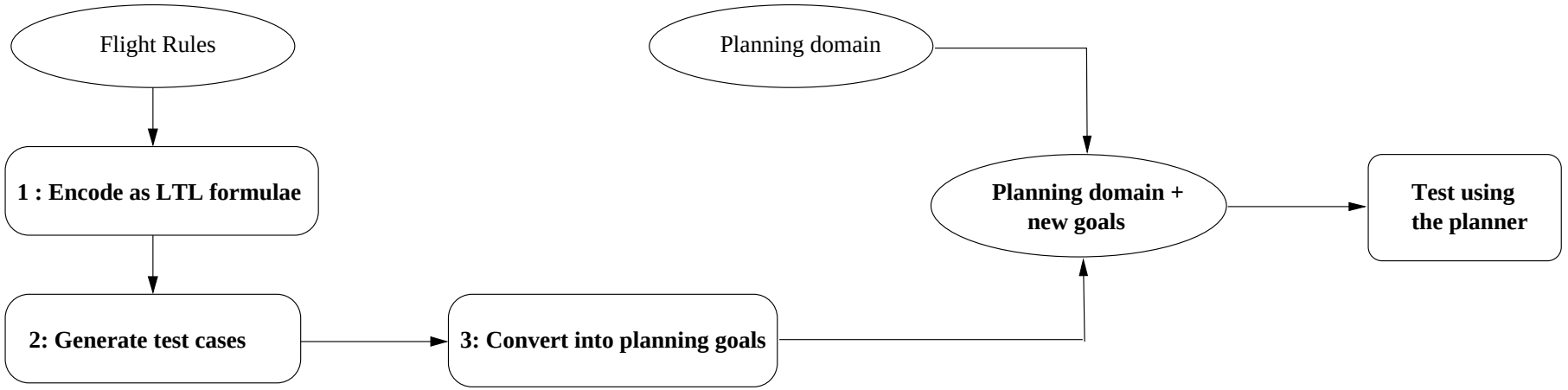
- Motivational introduction
- Flight rules
- Review of MC/DC and definition of UFC with weak/strong coverage.
- Planning: Europa 2 and NDDL
- The Rover Example: NDDL code, flight rules and trap formulae.
- From trap formulae to planning goals.
- Conclusion.

Motivation

- Planner are used extensively in a number of autonomous applications (e.g., the NASA rovers exploring Mars' surface).
- Methodology are needed to verify that certain requirements (the *flight rules*) are not violated when executing plans.
- Verification of planning domain has been investigated in the past by translating planning models into input for model checkers (but problems with state space explosion).

Our contribution

Key idea: translate the verification problem into a planning problem.



Flight rules

- Flight rules are requirements that must be satisfied in every execution (currently written in plain English).
- Typically, flight rules are *temporal patterns* and can be encoded as LTL formulae.
- Example: *all Instruments must be stowed when moving*, which is translated into $\varphi = G(\text{moving} \rightarrow \text{stowed})$

NEXT: How to build a suitable set of test cases to guarantee coverage of the above by extending MC/DC.

Brief overview of MC/DC (required coverage for avionic SW)

- Every basic condition in a decision in the model has taken on all possible outcomes at least once.
- Each basic condition has been shown to independently affect the decision's outcome.

An example: let $\varphi = p \vee q$. φ can be either true or false, and it can be so either because of p, or because of q. Test cases:

p	q	$p \vee q$
$\top$	$\bot$	$\top$
$\bot$	$\bot$	$\bot$
$\bot$	$\top$	$\top$

Each test case can be captured by a (Boolean) formula. Let φ^{pos} be the set of test cases for positive outcomes, and φ^{neg} the set for negative outcomes.

$\varphi^{pos} = \{p \wedge \neg q, \neg p \wedge q\}; \quad \varphi^{neg} = \{\neg p \wedge \neg q\}.$

Unique First Cause coverage

[Whalen et al., 2006] UFC extends MC/DC to requirements based testing (i.e., testing flight rules).

A test suite achieve UFC of a set of requirements (expressed in LTL) if:

1. Every basic condition in any formula has taken on all possible outcomes at least once.
2. Each basic condition has been shown to affect the formula's outcome as the *unique* first cause.

A basic condition a is the UFC for a formula φ along a path π if, in the first state along π in which φ is satisfied, it is satisfied because of a (see paper for a formal definition).

Trap formulae

[Whalen et al., 2006] A *trap formula* $ufc(a, \varphi)$ is a temporal formula characterising adequate test cases for a in φ.

$$ufc(a, a) = a; ufc(a, \neg a) = \neg a$$
$$ufc(a, \varphi_a \vee \varphi_b) = ufc(a, \varphi_a) \wedge \neg \varphi_b$$
$$ufc(a, \mathsf{F}\, \varphi_a) = (\neg \varphi_a)\, \mathsf{U}\, ufc(a, \varphi_a)$$
$$ufc(a, \mathsf{G}\, \varphi_a) = \varphi_a\, \mathsf{U}\, (ufc(a, \varphi_a) \wedge \mathsf{G}\, \varphi_a)$$

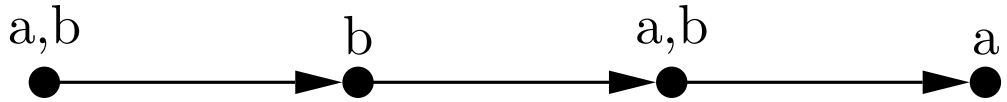
Problem: this only applies to *infinite* paths. If tests (paths) need to be finite, we need to change this definition.

Strong and weak UFC coverage

A finite path (test case) π_f gives:

1. *strong* evidence for φ (written as $\pi_f \models^+ \varphi$) if π_f "carries all necessary evidence for" φ;
2. *weak* evidence for φ (written as $\pi_f \models^- \varphi$) if π_f "carries no evidence against" φ;

Example: a strong test case for a in $\mathsf{F}\,(a \wedge \neg b)$ and a weak test case for a is $\mathsf{G}\,(a \vee b)$.



(see paper for the formal definition of $ufc^{\pm}$)

Summary of UFC

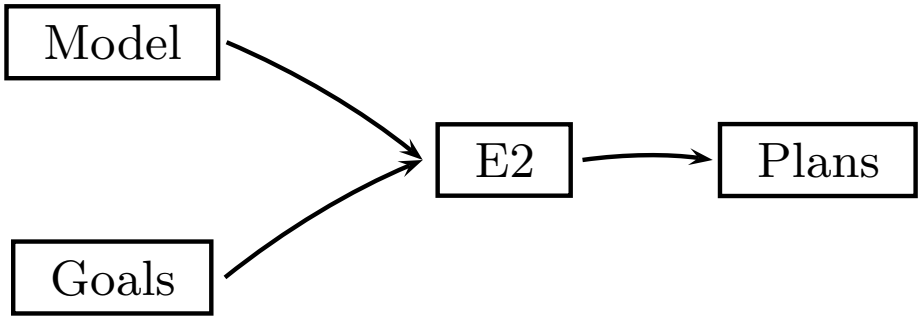
Given an atomic condition a appearing in a formula φ (a requirement) and an execution model M:

- if there is a test case $\pi_f \models ufc^{+}(a, \varphi)$ in the traces of M, then π_f shows that a can *necessarily* positively affect φ;
- if $\pi_f \models ufc^{-}(a, \varphi)$, then π_f only shows that a can *possibly* positively affect φ;
- if there is no π_f in M for which $\pi_f \models ufc^{\pm}(a, \varphi)$: if φ is a desired property, then this means that a is a *vacuous* condition in φ w.r.t. M;
- if φ is a negative (forbidden) property, then it confirms that this particular case of φ cannot happen, which is the desired result;
- A test fails if it is possible to find a path π_f in M such that $\pi_f \models ufc^{\pm}(a, \varphi)$, where φ is a negative property.

Planning with EUROPA 2.0 (E2)

[Excerpts from C. McGann, *How to Solve It*]

"*Planning can be considered a process of generating descriptions of how to operate some system to accomplish something. The resulting descriptions are called* **plans**, *and the desired accomplishments are called* **goals**. *In order to generate plans for a given system a* **model** *of how the system works must be given.*"

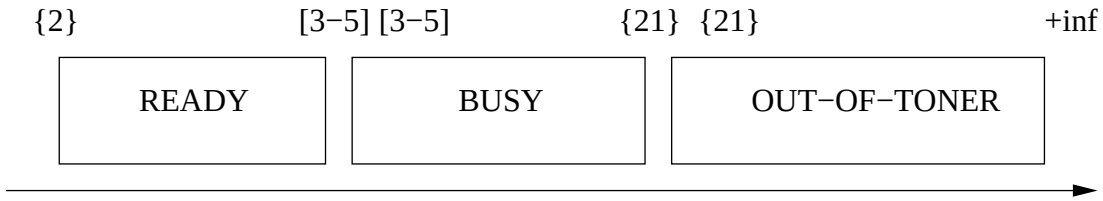


Models and goals are written in NDDL (see below).

Tokens and Timelines

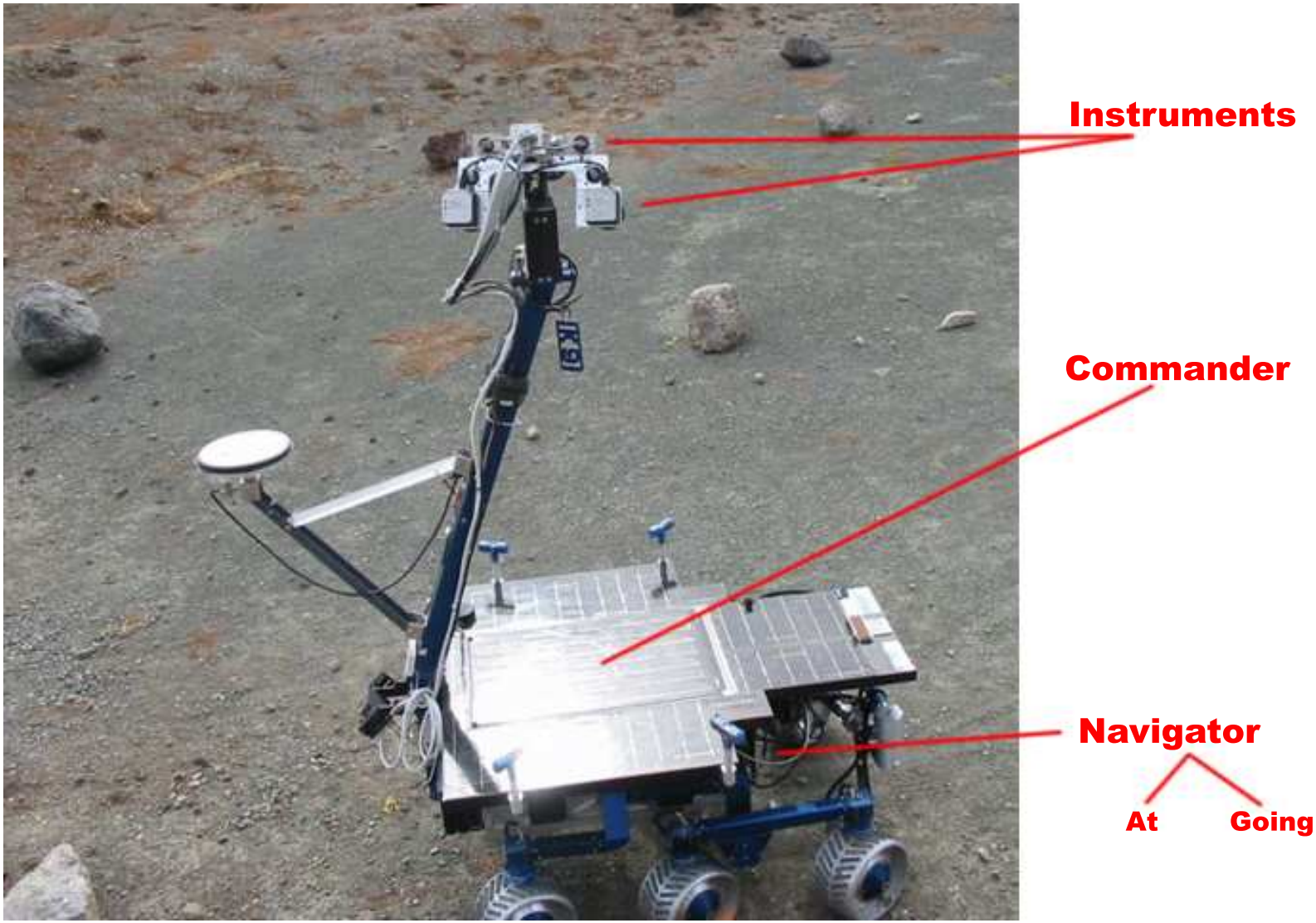
A **token** is "*an instance of a temporally scoped predicate*" (predicates describe true facts). For instance:

Tokens may represent states of a single object in the system, and are sometimes mutually exclusive. A **Timeline** is a structure where sequences of tokens appear contiguously. For instance, the state of a printer:

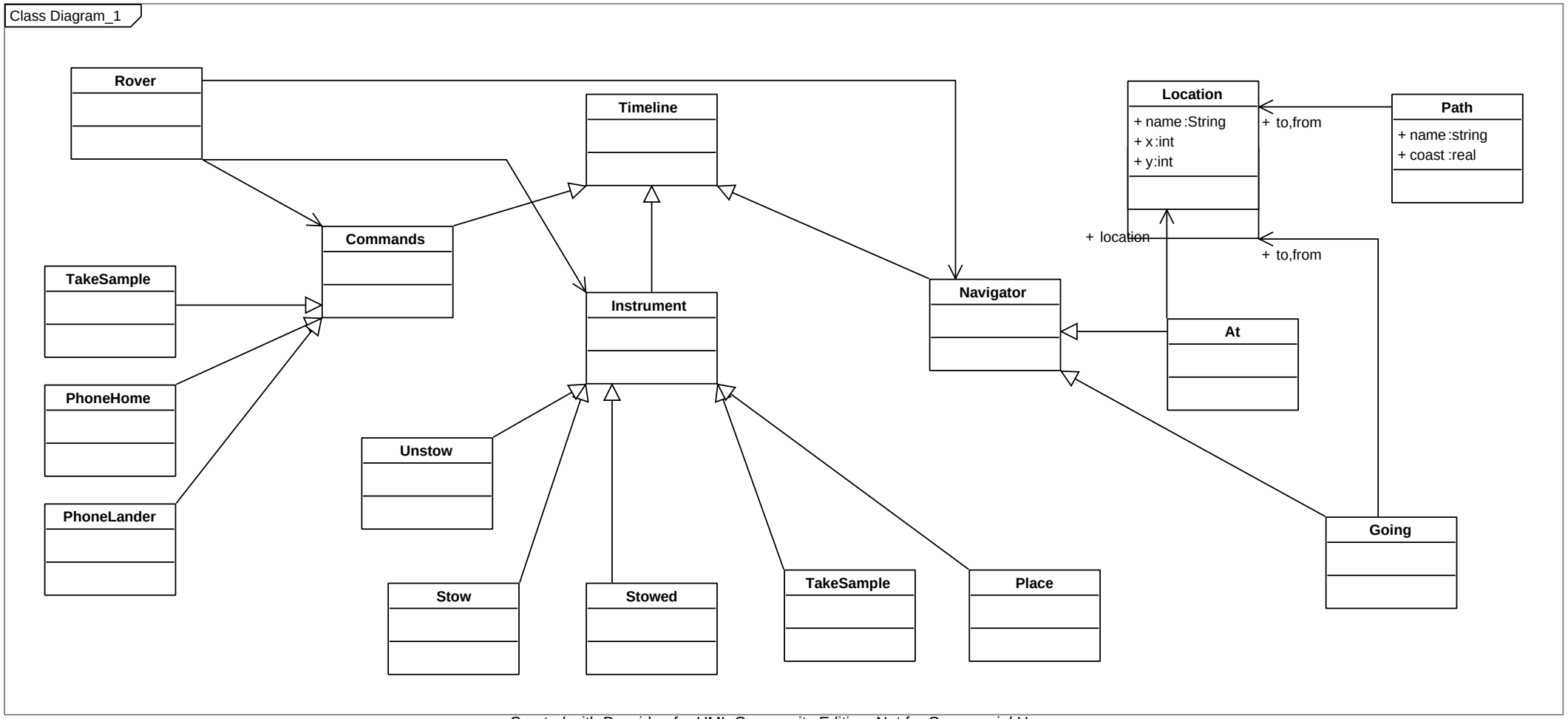


Constraints (rules) are expressed using Allen's temporal logic constructs, such as "meets", "met by", etc. Essentially, these are (in)equalities over tokens' bounds.

NDDL using an example: simple Rover model



NDDL using an example: simple Rover model



Some NDDL

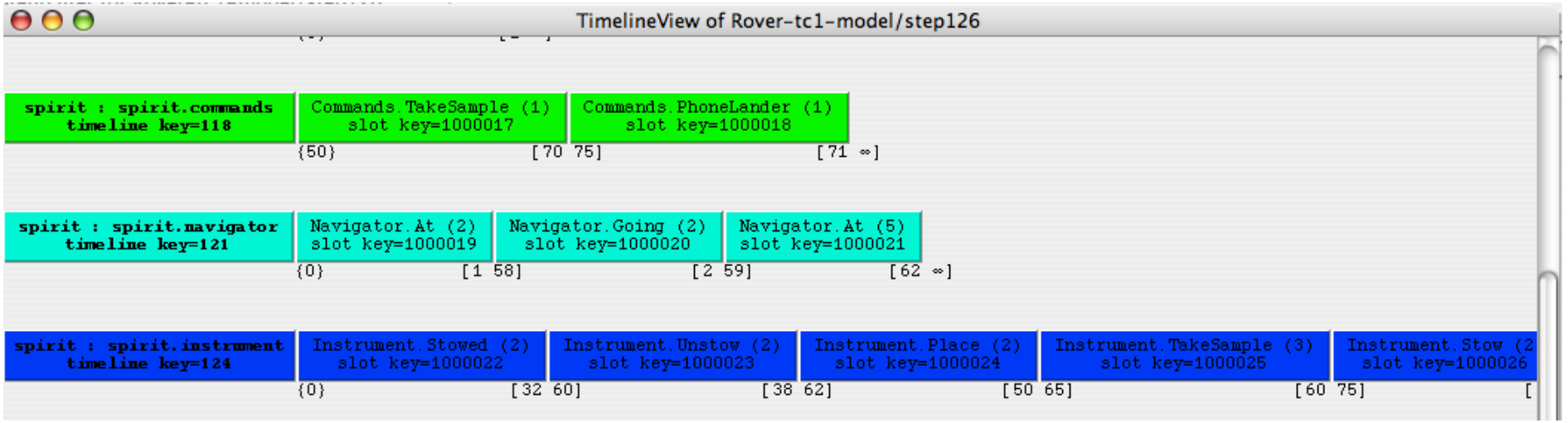
```
class Navigator extends Timeline {
 predicate At{
   Location location;
 }
 predicate Going{
   Location from;
   Location to;
   neq(from, to);
// prevents rover from going from a location straight back to that location.
 }
}
```

Tokens are constrained using *rules*:

```
Navigator::At{
  met_by(object.Going from);
  eq(from.to, location); // next Going token starts at this location
  meets(object.Going to);
  eq(to.from, location); // prevous Going token ends at this location
}
```

NDDL goals and executions

```
Location lander = new Location("LANDER", 0, 0);
[...]
goal(Navigator.At initialPosition);
eq(initialPosition.location, lander);
goal(Commands.TakeSample sample);
sample.start.specify(50);
sample.rock.specify(rock4);
```



A concrete example: flight rules for the rover

1. The Rover Battery State of charge cannot go below X.
2. All Instruments must be stowed when moving.
3. ...

In LTL:

1. $\mathsf{G}\,(x)$, where x is a proposition true when the charge is $\geq X$.
2. $\mathsf{G}\,(p \rightarrow q)$, where p = moving and q = stowed.
3. ... (translation done similarly).

We now apply the machinery presented above to compute test cases for the second requirement, $\mathsf{G}\,(p \rightarrow q)$.

Test cases for a flight rule

Three test cases for the formula:

1. (true value caused by "stowed"):
   $ufc^{-}(q, \varphi) = ((\neg p \wedge q) U (\neg p \wedge \neg q))$;
2. (true value caused by "moving"):
   $ufc^{-}(p, \varphi) = ((\neg p \wedge q) U (p \wedge q \wedge \varphi))$;
3. (this is the negative test case):
   $ufc^{+/-}(p, \neg\varphi) = ufc^{+/-}(q, \neg\varphi) = ((\neg p \vee q) U (p \wedge \neg q))$

Summary of coverage

- A model for the Rover (NDDL file).
- Flight rules encoded in LTL, for instance
  $\varphi = G(moving \rightarrow stowed)$.
- Trap formulae for flight rules that guarantee coverage.

Next step: *translation of elements of* $ufc^{\pm}$ *into planning goals*, so that E2 can be used *for testing flight rules.*

This is done without modification of the original NDDL model, by adding new timelines, new rules and new goals

Details of the translation into planning goals

- Introduce new timelines for Boolean components of a formula.
- A bottom-up translation, starting from the atoms and building negations, conjunction, disjunctions, etc.
- Temporal operators are translated into goal for these new timelines.

Example: the first positive test case for φ of the previous slide: $(\neg p \wedge q) U (\neg p \wedge \neg q)$

Next slide: the NDDL code corresponding to proposition p (moving) and its relation with the token Going.

```
class Prop_p extends Timeline {
    predicate TRUE { };
    predicate FALSE { };
}

Prop_p::TRUE {
    // Used to populate timeline
    met_by(object.FALSE f1);
    meets(object.FALSE f2);
    Navigator nav;
    equals(Navigator.Going);
}

Prop_p::FALSE {
    met_by(object.TRUE f1);
    meets(object.TRUE f2);
}

Navigator::Going {
  // p is true when Navigator is Going
  Prop_p pp;
  equals(pp.TRUE);
}
```

Negations, conjunctions, etc

- Negations: a new timeline defined using a previous one with `equals` rules.
- Use conjunctions only.
- Encoding a conjunction: this requires some work:
  - First define a timeline with all the combinations of the values of the two conjunct timelines ($\top\top, \top\bot, \ldots$).
  - Use contains / contained_by to define tokens' relationships.
  - For the continuity of the timeline: use enumerations and match each predicate with all the other predicates

Temporal operators as goals

In the example: $(\neg p \wedge q) U (\neg p \wedge \neg q)$, i.e., `timeline1.TRUE` until `timeline2.TRUE`.

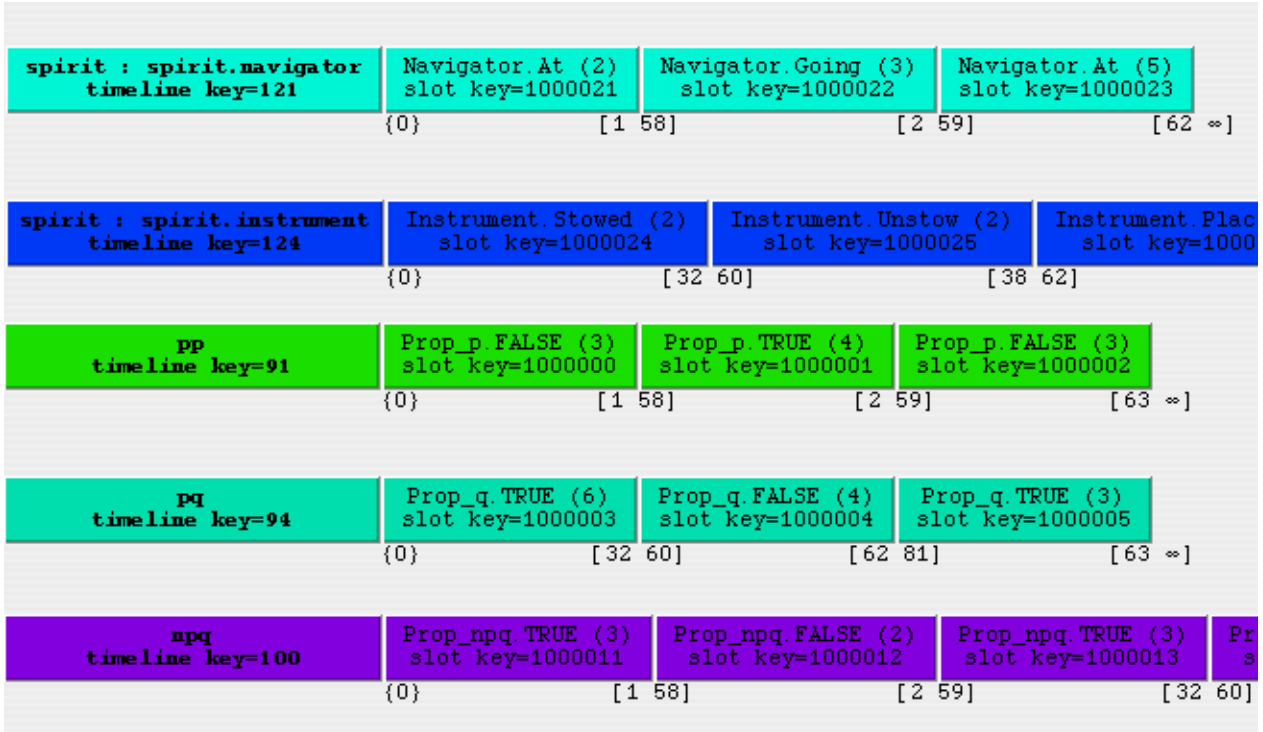
This is translated into:

```
timeline2.TRUE contains_end timeline1.TRUE
```

and other additional constraints (for initial states etc).

This is the actual code `<SWITCH DISPLAY>` to show *.nddl.

Running E2 with this code



(the important point here is: a plan can be obtained with the additional new constraints).

The negative test case:

(the important point here is: **no plan can be obtained**)

Conclusions

- Extension of UFC with definitions of strong/weak acceptance.
- A methodology to test flight rules
  - with coverage guarantees;
  - self-contained (no external tools);
  - using patterns, a tool could be implemented to perform tests automatically;
  - the new timelines+rules are *added* to the original model (i.e., the original model is not modified).
- Not a production scenario yet, but more complex than what can be done with model checkers.

Future work

- Nested temporal operators (flight rules analysed don't contain nested operators, but they could).
- Automatic tools to perform the translation NDDL + LTL into new NDDL code.
- A collection of patterns for flight rules and a graphical interface for plan developers.