Answer Set Programming for Stream Reasoning

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Outline

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Motivation

While traditional Answer Set Programming (ASP) methods aim at singular problem solving,

> *"stream reasoning, instead, restricts processing to a certain window of concern, focusing on a subset of recent statements in the stream, while ignoring previous statements"* [BBC+10].

Data stream management systems (for high-throughput stream processing) [GÖ10] lack complex reasoning capacities [DCvF09], as required in application areas like

- ambient assisted living,
- dynamic scheduling,
- robotics,
- etc.

Goal: Close gap by enriching ASP with means for stream reasoning**!**

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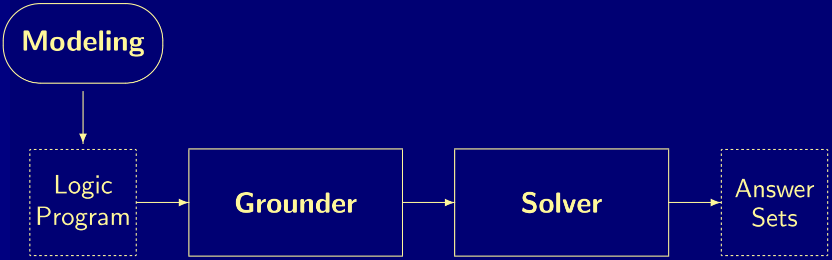
Setting the stage

Reactive ASP by `oclingo`



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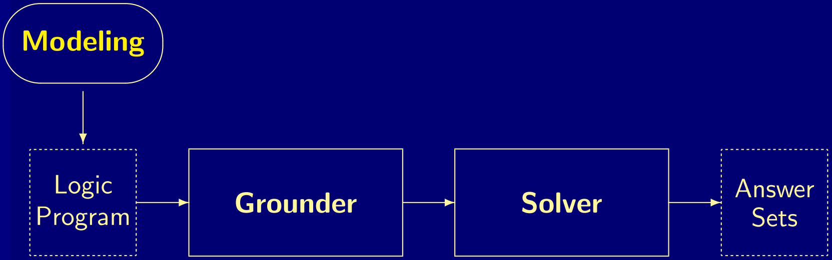

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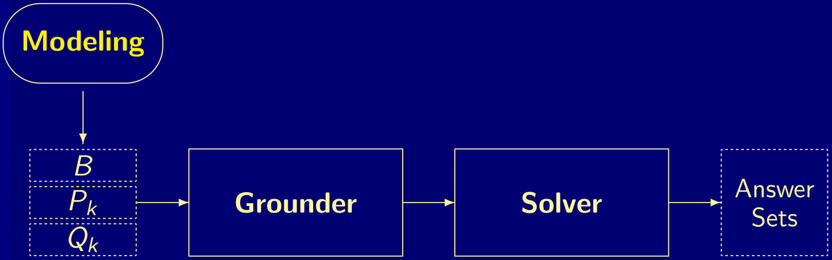

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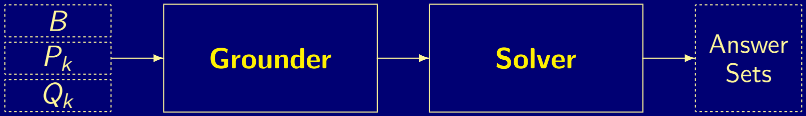

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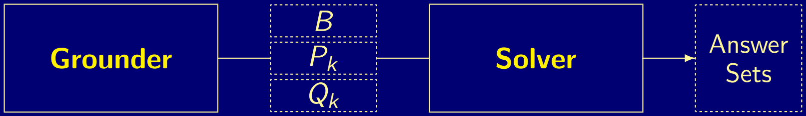

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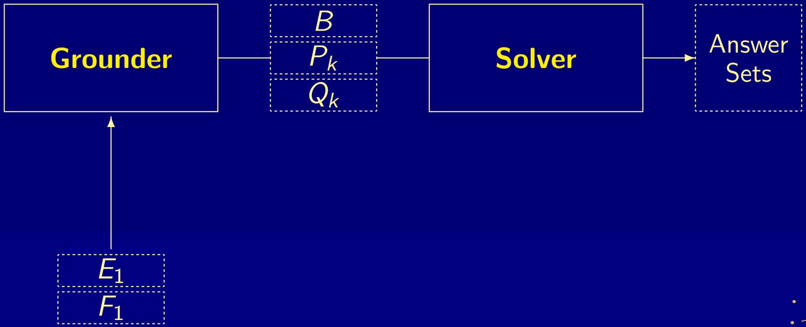

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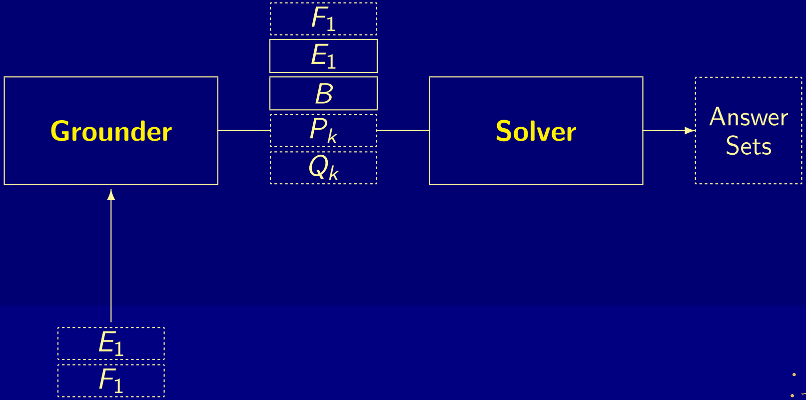

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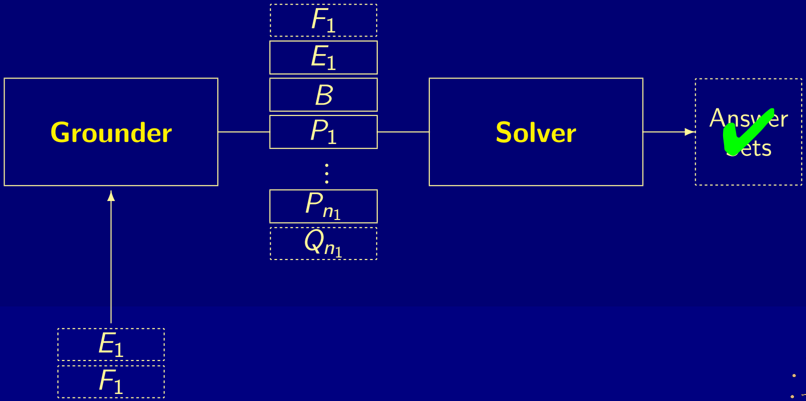

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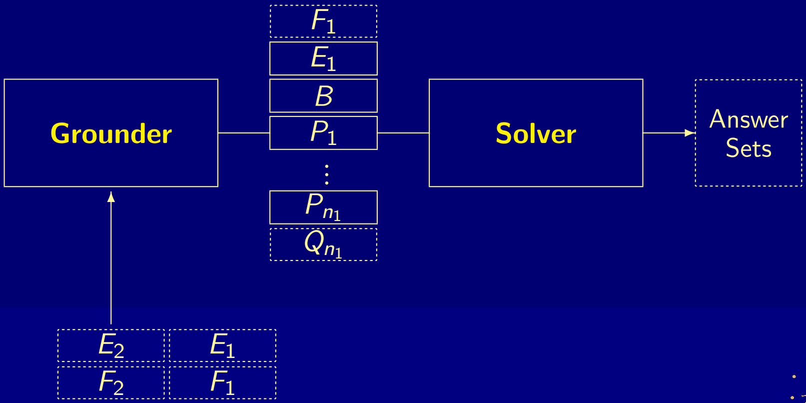

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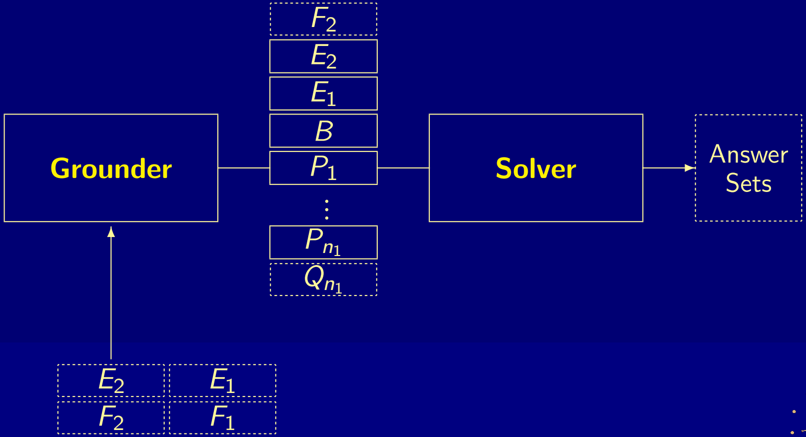

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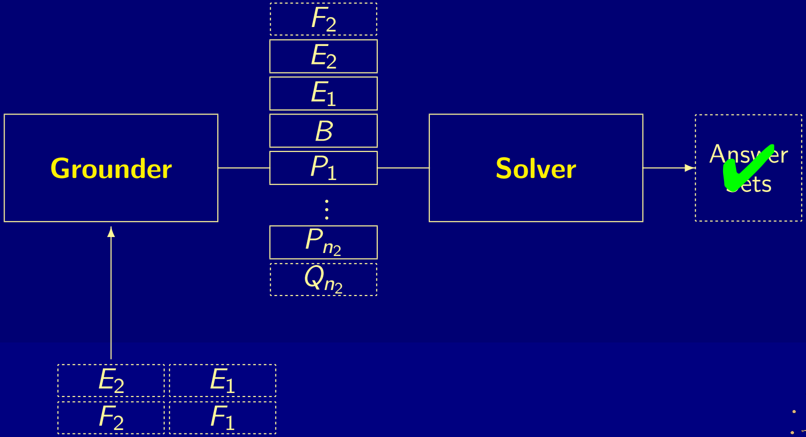

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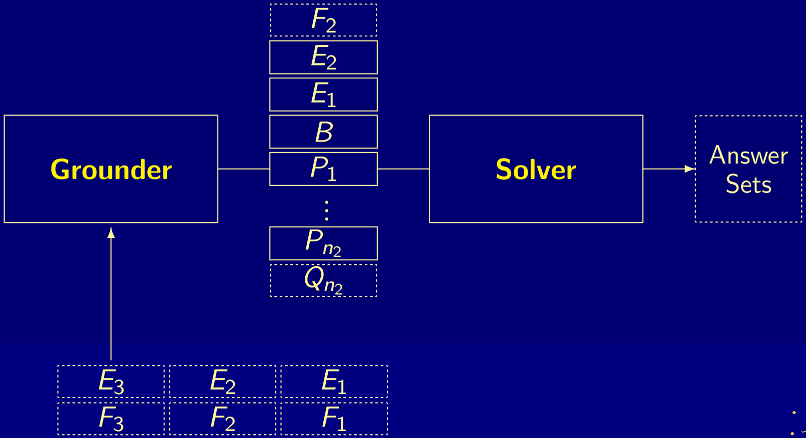

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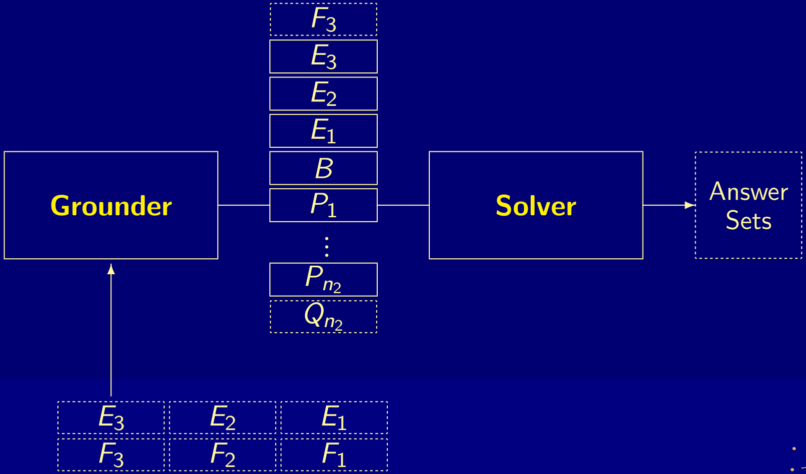

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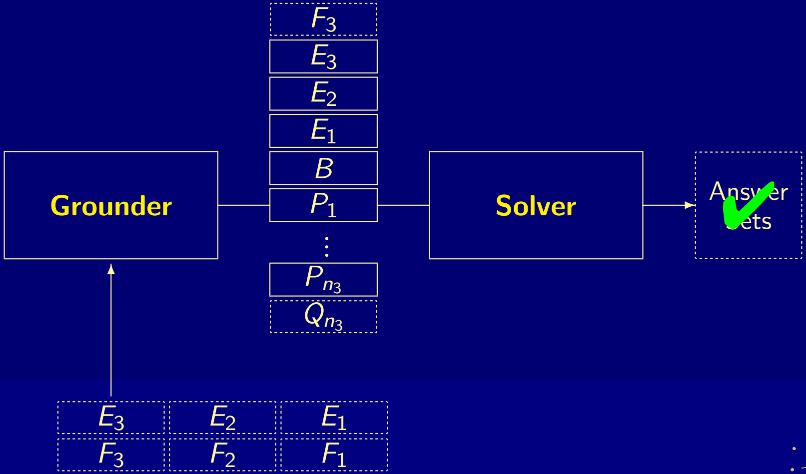

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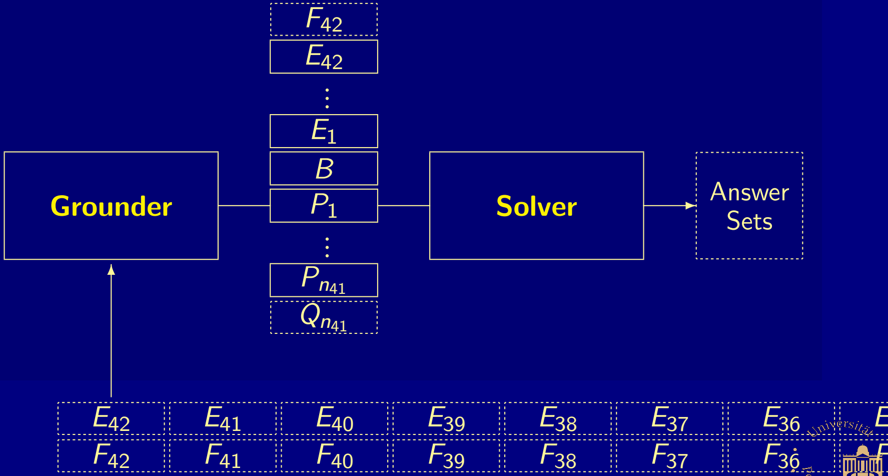

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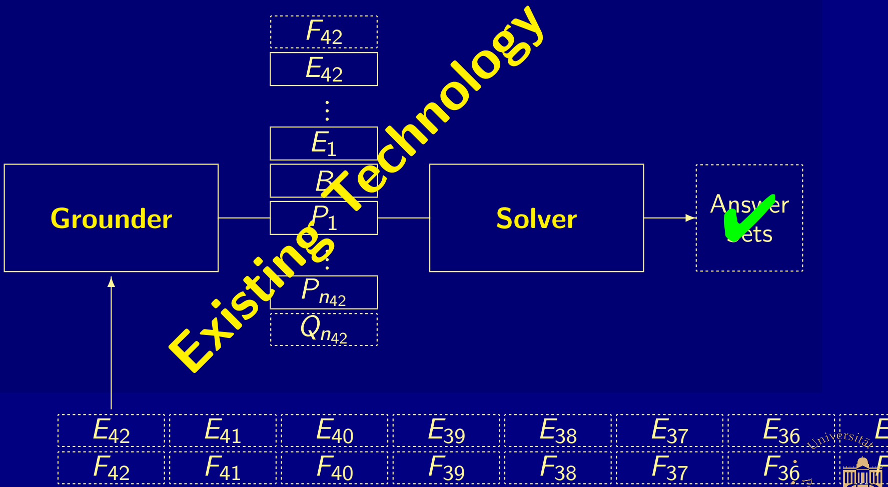

Outline

Running example

Consider the task of continuously matching stream prefixes against regular expression $(a|b)^*aa$.

Example Stream

$aabaaab\ldots$ ✘

Observation: Only the two last readings are significant.

➥ Restrict attention to sliding window of width 2**!**

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Limitations of (foregoing) reactive ASP I

Stream Data

```
#step 1.        #step 2.        #step 3.
read(a,1).      read(a,2).      read(b,3).      ...
#endstep.       #endstep.       #endstep.
```

Reactive ASP Encoding

```
#iinit 0.
#cumulative t.            #external read(a;b,t+1).
accept(t) :- read(a,t;t-1), not read(a;b,t+1).
```

Incremental Instantiation: $t = 0$

```
accept(0) :- read(a,0), read(a,-1),
          not read(a,1), not read(b,1).
```

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#step 1.        #step 2.        #step 3.
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```

Incremental Instantiation: $t = 1$

```
accept(1) :- read(a,1), read(a,0),
         not read(a,2), not read(b,2).
read(a,1).
```

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#step 1.        #step 2.        #step 3.
read(a,1).      read(a,2).      read(b,3).      ...
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Reactive ASP Encoding

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#iinit 0.
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accept(t) :- read(a,t;t-1), not read(a;b,t+1).
```

Incremental Instantiation: $t = 2$

```
accept(2) :- read(a,2), read(a,1),
             not read(a,3), not read(b,3).
read(a,1).   read(a,2).
```

Limitations of (foregoing) reactive ASP I

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#step 1.        #step 2.        #step 3.
read(a,1).      read(a,2).      read(b,3).      ...
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Reactive ASP Encoding

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#cumulative t.          #external read(a;b,t+1).
accept(t) :- read(a,t;t-1), not read(a;b,t+1).
```

Incremental Instantiation: $t = 3$

```
accept(3) :- read(a,3), read(a,2),
             not read(a,4), not read(b,4).
read(a,1).   read(a,2).   read(b,3).
```

Limitations of (foregoing) reactive ASP I

Stream Data

```
#step 1.        #step 2.        #step 3.
read(a,1).      read(a,2).      read(b,3).      ...
#endstep.       #endstep.       #endstep.
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```

Incremental Instantiation: $t = \ldots$

```
...
read(a,1).   read(a,2).   read(b,3).   ...
```

✘ Obsolete data is *not* erased!

Limitations of (foregoing) reactive ASP II

Stream Data

```
#step 1.        #step 2.        #step 3.
#volatile.      #volatile.      #volatile.
                read(a,1).      read(a,2).
read(a,1).      read(a,2).      read(b,3).     ...
#endstep.       #endstep.       #endstep.
```

Reactive ASP Encoding

```
#iinit 0.
#cumulative t.          #external read(a;b,t+1).
accept(t) :- read(a,t;t-1), not read(a;b,t+1).
```

- ✘ Data must be replayed!
- Redefinitions (of head atoms) violate modularity assumption.

Limitations of (foregoing) reactive ASP II

Stream Data

```
#step 1.
#volatile.

read(a,1).
#endstep.
```

```
#step 2.
#volatile.
read(a,1).
read(a,2).
#endstep.
```

```
#step 3.
#volatile.
read(a,2).
read(b,3).
#endstep.
```

...

Reactive ASP Encoding

```
#cumulative t.          #external read(a;b,t).
accept(t) :- read(a,t;t-1).
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```
#cumulative t.          #external read(a;b,t;t-1,t).
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Closing the gap

Review

Neither permanent ("**#cumulative**.") nor singular ("**#volatile**.") consideration of online data is suitable for stream reasoning.

Preview

Extend `oclingo` language by "**#volatile** : l." directive for built-in support of expiration in l steps.

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Extend `oclingo` language by "**#volatile** : l." directive for built-in support of expiration in l steps.

Closing the gap

Stream Data

```
#step 1.          #step 2.          #step 3.
#volatile : 2.    #volatile : 2.    #volatile : 2.
read(a,1).        read(a,2).        read(b,3).        ...
#endstep.         #endstep.         #endstep.
```

Reactive ASP Encoding

```
#cumulative t.          #external read(a;b,t).
accept(t) :- read(a,t;t-1).
```

Incremental Instantiation: $t = 1$

```
accept(1) :- read(a,1), read(a,0).
             read(a,1).
```

✔ Obsolete data is erased without necessitating replays!

Closing the gap

Stream Data

```
#step 1.         #step 2.         #step 3.
#volatile : 2.   #volatile : 2.   #volatile : 2.
read(a,1).       read(a,2).       read(b,3).       ...
#endstep.        #endstep.        #endstep.
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Reactive ASP Encoding

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#cumulative t.        #external read(a;b,t).
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#step 1.          #step 2.          #step 3.
#volatile : 2.    #volatile : 2.    #volatile : 2.
read(a,1).        read(a,2).        read(b,3).      ...
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accept(2) :- read(a,2), read(a,1).
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Stream Data

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#step 1.          #step 2.          #step 3.
#volatile : 2.    #volatile : 2.    #volatile : 2.
read(a,1).        read(a,2).        read(b,3).      ...
#endstep.         #endstep.         #endstep.
```

Reactive ASP Encoding

```
#cumulative t.          #external read(a;b,t).
accept(t) :- read(a,t;t-1).
```

Incremental Instantiation: $t = 3$

```
accept(3) :- read(a,3), read(a,2).
             read(b,3). read(a,2).
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Closing the gap

Stream Data

```
#step 1.          #step 2.          #step 3.
#volatile : 2.    #volatile : 2.    #volatile : 2.
read(a,1).        read(a,2).        read(b,3).      ...
#endstep.         #endstep.         #endstep.
```

Reactive ASP Encoding

```
#cumulative t.          #external read(a;b,t).
accept(t) :- read(a,t;t-1).
```

Incremental Instantiation: $t = \ldots$

```
accept(t) :- read(a,t), read(a,t-1).
             read(_,t). read(_,t-1).
```

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Outline

Recapitulation

We have seen how an reactive ASP encoding can be expanded relative to sliding window data by successively

1. generating new (ground) rules
2. defining new (ground) atoms.

✘ New propositions handicap the re-use of conflict constraints.

In what follows, we develop modeling approaches to combine online data with a static problem representation.

Idea: Encode problem wrt. any window contents and dynamically map stream data (in window) to internal representation!

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Modified running example

Consider the task of checking whether the last five readings (over alphabet $\{a, b\}$) from a stream include *aaa* as a subsequence.

Example Stream

$aabaaab\ldots$ ✘

$\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\ \downarrow$

$1234567\ldots$

Observation: Readings remain in window for five steps.

➥ Map stream positions to slots represented by remainders of 5**?**

✘ Circular subsequences may lead to false positives.

Idea: Introduce a free slot to disconnect present from past data**!**

Static problem representation captures windows of width 5.

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↧↧↧↧↧↧↧ ↧

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Static problem representation captures windows of width 5.

Modified running example

Consider the task of checking whether the last five readings (over alphabet $\{a, b\}$) from a stream include aaa as a subsequence.

Example Stream

$aabaaab\ldots$ ✔

↧↧↧↧↧↧↧ ↧

$1234567\ldots$

Observation: Readings remain in window for five steps.

➥ Map stream positions to slots represented by remainders of 5**?**

✘ Circular subsequences may lead to false positives.

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Modified running example

Consider the task of checking whether the last five readings (over alphabet $\{a, b\}$) from a stream include *aaa* as a subsequence.

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↧↧↧↧↧↧↧ ↧

$1234012\ldots$

Observation: Readings remain in window for five steps.

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$\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\ \downarrow$

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Modified running example

Consider the task of checking whether the last five readings (over alphabet $\{a, b\}$) from a stream include aaa as a subsequence.

Example Stream

$aabaaab\ldots$ ✘

↧↧↧↧↧↧↧ ↧

$1234501\ldots$

Observation: Readings remain in window for five steps.

➥ Map stream positions to slots represented by remainders of 5?

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Consider the task of checking whether the last five readings (over alphabet $\{a, b\}$) from a stream include aaa as a subsequence.

Example Stream

$aabaaab\ldots$

$\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\ \downarrow$

$1234501\ldots$

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Static "free slot" approach

Reactive ASP Encoding

```
#base.
next(T,(T+1) #mod 6) :- T := 0..5.
{ b_read(a,T) } :- next(T,_).
single(T) :- b_read(a,T).
double(T) :- b_read(a,T), single(S), next(S,T).
accept    :- b_read(a,T), double(S), next(S,T).
```

- Static program part is instantiated once (initially).
- Successive slots are determined via modulo-6 arithmetic.
- Internal representation of readings is generated by choice rules.
- Subsequences *aaa* are traced wrt. internal representation.

➥ Dynamic parts must map readings to internal representation!

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```

Ground Instantiation

```
next(0,1).   next(3,4).
next(1,2).   next(4,5).
next(2,3).   next(5,0).
```

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Online data vs. internal representation

Stream Data

```
#step 1.            #step 2.            #step 3.
#volatile : 5.      #volatile : 5.      #volatile : 5.
read(a,1).          read(a,2).          read(b,3).      ...
#endstep.           #endstep.           #endstep.
```

read ⇒ b_read

```
#cumulative t.            #external read(a;b,t).
:- read(a,t), not b_read(a,t #mod 6).
```

b_read ⇒ read

```
#volatile t : 6.
:- b_read(a,t #mod 6), not read(a,t).
```

➥ Constraints expire when window progresses (by six steps).

Online data vs. internal representation

Stream Data

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#step 1.          #step 2.          #step 3.
#volatile : 5.    #volatile : 5.    #volatile : 5.
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```

b_read ⇒ read

```
#volatile t : 6.        #iinit -4.
:- b_read(a,(t+6) #mod 6), not read(a,t).
```

➥ Window is filled at step 1 to avoid guesses (over b_read).

Online data vs. internal representation

Stream Data

```
#step 1.          #step 2.          #step 3.
#volatile : 5.    #volatile : 5.    #volatile : 5.
read(a,1).        read(a,2).        read(b,3).        ...
#endstep.         #endstep.         #endstep.
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```

Observation: Dynamic parts confined to data and its mapping.

Remodified running example

Consider the task of checking whether the last five readings (over an arbitrary alphabet) include at least three occurrences of letter *a*.

➥ We may use frame axioms [Lif02] in the static program part.

Reactive ASP Encoding with Frame Axioms

```
#base.
next(T,(T+1) #mod 5) :- T := 0..4.
{ b_read(a,T) } :- next(T,_).
single(T) :- b_read(a,T).
double(T) :- b_read(a,T), single(S), next(S,T).
accept    :- b_read(a,T), double(S), next(S,T).
single(T) :- single(S), next(S,T).
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Observation: Frame axioms propagate into the past (via `next`).

Idea: Introduce a predicate to disconnect present from the past!

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Static "last slot" approach

Reactive ASP Encoding with Frame Axioms

```
#base.                    slot(0..4).
next(T,(T+1) #mod 5) :- T := 0..4.
{ b_read(a,T) } :- next(T,_).
single(T) :- b_read(a,T).
double(T) :- b_read(a,T), single(S), next(S,T).
accept    :- b_read(a,T), double(S), next(S,T).
single(T) :- single(S), next(S,T).
double(T) :- double(S), next(S,T).
{ now(T) : slot(T) } 1.
#volatile t.
:- not now(t #mod 5).
```

➥ Propagation beyond the current slot is suppressed (via `now`).

Static "last slot" approach

Reactive ASP Encoding with Frame Axioms

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#base.                           slot(0..4).
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Outline

Summary

We have

1. extended `oclingo` by built-in support of sliding windows and
2. developed modeling approaches to reason over transient data.

To promote the re-use of conflict constraints, we proposed to

1. statically encode a task wrt. any window contents and
2. dynamically map stream data to its designated representation.

We demonstrated how to preserve the chronology of data via

1. a free slot in the static program part or
2. a predicate qualifying the current slot.

↪ Beyond simple illustration domains [GGK+12a, GGK+12b], the presented modeling approaches are of general applicability, especially to solve combinatorial problems wrt. stream data.

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Outlook

While ASP offers interesting prospects for knowledge-intense stream reasoning, continuous settings impose particular challenges.

- Improved low-level support of data expiration is needed to avoid memory pollution.
- Yet missing sequential functionalities, such as optimization, must be supplied to incremental and reactive operation modes.
- Provision of handy high-level language constructs is desirable to facilitate the modeling of sliding window scenarios by users.
- Additional control directives, such as **#assert** and **#retract**, may be useful to flexibly (de)activate logic program parts.

This work is only a first step towards ASP-based stream reasoning.

➥ Realistic applications must be pioneered to furnish a deeper understanding and advanced system support of use cases.

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