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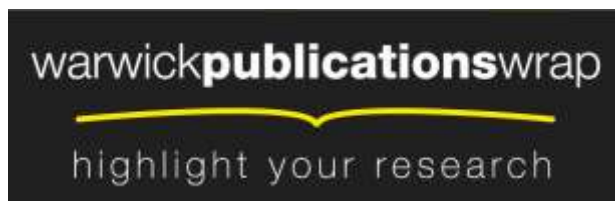
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# Non-Elementary Complexities for Branching VASS, MELL, and Extensions \*

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## Abstract

We study the complexity of reachability problems on branching extensions of vector addition systems, which allows us to derive new non-elementary complexity bounds for fragments and variants of propositional linear logic. We show that provability in the multiplicative exponential fragment is TOWER-hard already in the affine case—and hence non-elementary. We match this lower bound for the full propositional affine linear logic, proving its TOWER-completeness. We also show that provability in propositional contractive linear logic is ACKERMANN-complete.

**Categories and Subject Descriptors** F.2.2 [Analysis of Algorithms and Problem Complexity]: Nonnumerical Algorithms and Problems—Complexity of proof procedures; F.4.1 [Mathematical Logic and Formal Languages]: Mathematical Logic

**General Terms** Theory

**Keywords** Fast-growing complexity, linear logic, substructural logic, vector addition systems.

## 1. Introduction

The use of various classes of counter machines to provide computational counterparts to propositional substructural logics has been highly fruitful, allowing to prove for instance:

- the undecidability of provability in propositional linear logic (LL), thanks to a reduction from the halting problem in Minsky machines proved by Lincoln, Mitchell, Scedrov, and Shankar [14], who initiated much of this line of work,
- the decidability of the !-Horn fragment of multiplicative exponential linear logic, proved by Kanovich [9] by reduction to reachability in vector addition systems,
- the decidability of provability in affine linear logic, first shown by Kopylov using a notion of vector addition games [10],
- the ACKERMANN-completeness of provability in the conjunctive implicative fragment of relevance logic, proved by

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Urquhart [23], using reductions to and from expansive alternating vector addition systems, and

- the inter-reducibility between provability in multiplicative exponential linear logic and reachability in a model of branching vector addition systems, shown by de Groote, Guillaume, and Salvati [5].

### 1.1 Alternating Branching VASS

In this paper, we revisit the correspondences between propositional linear logic and counter systems with a focus on computational complexity. In Section 3, we define a model of *alternating branching vector addition systems* (ABVASS) with *full zero tests*. While this model can be seen as an extension and repackaging of Kopylov's vector games, its reachability problem enjoys very simple reductions to and from provability in LL, which are suitable for complexity statements (see Section 4). We prove that:

- coverability in the top-down, root-to-leaves direction is TOWER-complete, i.e. complete for the class of problems that can be solved with time or space resources bounded by a tower of exponentials whose height depends elementarily in the input size (see Section 5 for the upper bound and Section 6 for the lower bound), and
- coverability in the bottom-up, leaves-to-root direction is complete for ACKERMANN, i.e. complete for resources bounded by the Ackermann function of some primitive-recursive function of the input.

Due to space constraints, the technical details for this second point are omitted in this paper but can be found along with other material in the full paper at the address <http://arxiv.org/abs/1401.6785>.

### 1.2 Provability in Substructural Logics

Our complexity bounds for ABVASS translate into the exact same bounds for provability in fragments and variants of LL:

#### 1.2.1 Affine Linear Logic

Affine Linear Logic (LLW) was proved decidable by Kopylov [10] in 1995 using vector addition games; a model-theoretic proof was later presented by Lafont [11].<sup>1</sup>

The best known complexity bounds for LLW are due to Urquhart [24]: by a reduction from coverability in vector addition systems [15], he derives an EXPSPACE lower bound, very far from

<sup>1</sup> Variants of LLW are popular in the literature on implicit complexity; for instance, *light affine linear logic* [1] is known to type exactly the class FP of polynomial time computable functions. In this paper we are however interested in the complexity of the provability problem (for the propositional fragment), rather than the complexity of normalization. In terms of typed lambda calculi, our results pertain to the complexity of the type inhabitation problem.

the ACKERMANN upper bound he obtains from length function theorems for Dickson’s Lemma [see e.g. 8].

### 1.2.2 Contractive Linear Logic

Contractive Linear Logic (LLC) was proved decidable by Okada and Terui [17] by model-theoretic methods.

Urquhart [23] showed the ACKERMANN-completeness of provability in a fragment of relevance logic, which is also a fragment of intuitionistic multiplicative additive LLC. To the best of our knowledge, there are no known complexity upper bounds for provability in LLC.

### 1.2.3 Multiplicative Exponential Linear Logic

The main open question in this area is whether the multiplicative exponential fragment (MELL) is decidable. It is related to many decision problems, for instance in computational linguistics [19, 20], cryptographic protocol verification [25], the verification of parallel programs [3], and data logics [2, 7].

Thanks to the reductions to and from the reachability problem in branching vector addition systems with states (BVASS) [5] and to the bounds of Lazić [13], we know that provability in MELL is 2-EXPSpace-hard.

### 1.2.4 Summary of the Complexity Results

**LLW** We improve both the lower bound and the upper bound of Urquhart [24], and prove that LLW provability is complete for TOWER.

**LLC** We show that LLC provability is ACKERMANN-complete; the lower bound already holds for the multiplicative additive fragment MALLC.

**MELL** Our TOWER-hardness result for LLW already holds for affine MELL and thus for MELL, which improves over the 2-EXPSpace lower bound of Lazić [13].

**ILL** All of our complexity bounds also hold for provability in the intuitionistic versions of our calculi. See the full paper for details.

## 2. Propositional Linear Logic

### 2.1 Classical Linear Logic

For convenience, we present here a sequent calculus for classical propositional linear logic that works with formulæ in negation normal form and considers one-sided sequents.

#### 2.1.1 Syntax

Propositional linear logic formulæ are defined by the abstract syntax

$$\begin{array}{ll}
A, B ::= a \mid a^\perp & \text{(atomic)} \\
\mid A \wp B \mid A \otimes B \mid \perp \mid \mathbf{1} & \text{(multiplicative)} \\
\mid A \& B \mid A \oplus B \mid \top \mid \mathbf{0} & \text{(additive)} \\
\mid !A \mid ?A & \text{(exponential)}
\end{array}$$

where  $a$  ranges over atomic formulæ. We write “ $A^\perp$ ” for the negation normal form of  $A$ , where negations are pushed to the atoms using the dualities  $A^{\perp\perp} = A$ ,  $(A \wp B)^\perp = A^\perp \otimes B^\perp$ ,  $\perp^\perp = \mathbf{1}$ ,  $(A \& B)^\perp = A^\perp \oplus B^\perp$ ,  $\top^\perp = \mathbf{0}$ , and  $(?A)^\perp = !A^\perp$ . We write “ $A \multimap B$ ” for the linear implication  $A^\perp \wp B$ .

#### 2.1.2 Sequent Calculus

The rules of the sequent calculus manipulate multisets of formulæ, denoted by  $\Gamma, \Delta, \dots$ , so that the exchange rule is implicit; “ $? \Gamma$ ”

then denotes a multiset of formulæ all guarded by why-nots:  $? \Gamma$  is of the form  $?A_1, \dots, ?A_n$ .

$$\begin{array}{c}
\frac{}{\vdash A, A^\perp} \text{init} \quad \frac{\vdash \Gamma, A \quad \vdash \Delta, A^\perp}{\vdash \Gamma, \Delta} \text{cut} \\
\frac{\vdash \Gamma, A, B}{\vdash \Gamma, A \wp B} \wp \quad \frac{\vdash \Gamma, A \quad \vdash \Delta, B}{\vdash \Gamma, \Delta, A \otimes B} \otimes \quad \frac{\vdash \Gamma}{\vdash \Gamma, \perp} \perp \quad \frac{}{\vdash \mathbf{1}} \mathbf{1} \\
\frac{\vdash \Gamma, A \quad \vdash \Gamma, B}{\vdash \Gamma, A \& B} \& \quad \frac{\vdash \Gamma, A \quad \vdash \Gamma, B}{\vdash \Gamma, A \oplus B} \oplus \quad \frac{}{\vdash \Gamma, \top} \top \\
\frac{\vdash \Gamma, A}{\vdash \Gamma, ?A} ?D \quad \frac{\vdash \Gamma}{\vdash \Gamma, ?A} ?W \quad \frac{\vdash \Gamma, ?A, ?A}{\vdash \Gamma, ?A} ?C \quad \frac{\vdash ?\Gamma, A}{\vdash ?\Gamma, !A} ?P
\end{array}$$

The last four rules for exponential formulæ are called *dereliction* (?D), *logical weakening* (?W), *logical contraction* (?C), and *promotion* (?P).

The *cut* rule can be eliminated in this calculus, which then enjoys the *subformula property*: in any rule except cut, the formulæ appearing in the premises are subformulæ of the formulæ appearing in the conclusion.

### 2.2 Fragments and Variants

Lincoln et al. [14] established most of the results on the decidability and complexity of provability in propositional linear logic. In particular, the full propositional linear logic (LL) is undecidable, while its multiplicative additive fragment (MALL, which excludes the exponential connectives and rules) is decidable in PSPACE. As mentioned in the introduction, the main open question in this area is whether the multiplicative exponential fragment (MELL, which excludes the additive connectives and rules) is decidable.

Regarding related logics, allowing respectively *structural weakening* (W) and *structural contraction* (C)

$$\frac{\vdash \Gamma}{\vdash \Gamma, A} W \quad \frac{\vdash \Gamma, A, A}{\vdash \Gamma, A} C$$

instead of logical weakening and logical contraction gives rise to two decidable variants, called respectively *affine* linear logic (LLW) and *contractive* linear logic (LLC). The sequent calculi for LLW and LLC also enjoy cut elimination and the subformula property for cut-free proofs. We consider the intuitionistic variants of LL, LLW, and LLC in the full paper.

## 3. Alternating Branching VASS

We define a “tree” extension of vector addition systems with states (VASS) that combines two kinds of branching behaviors: those of alternating VASS (Section 3.3.1) and those of branching VASS (Section 3.3.2). With this combination, we obtain a reformulation of Kopylov’s vector addition games [10], for which he showed that

1. the game is inter-reducible with LL provability
2. the “lossy” version of the game is inter-reducible with LLW provability.

We further add *full zero tests* to this model, as they make the reduction from LL provability straightforward (see Section 4) and can easily be removed (see Section 3.3.3).

### 3.1 Definitions

#### 3.1.1 Syntax

An *alternating branching vector addition system with states and full zero tests* (ABVASS<sub>0</sub>) is a tuple  $\mathcal{A} = \langle Q, d, T_u, T_f, T_s, T_z \rangle$  where  $Q$  is a finite set of *states*,  $d$  is a *dimension* in  $\mathbb{N}$ , and  $T_u \subseteq Q \times \mathbb{Z}^d \times Q$ ,  $T_f \subseteq Q^3$ ,  $T_s \subseteq Q^3$  and  $T_z \subseteq Q^2$  are respectively finite sets of *unary*, *fork*, *split* and *full zero test* rules.

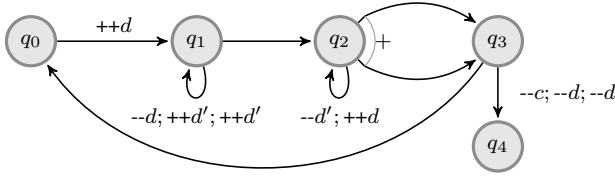


Figure 1. An example BVASS.

We denote unary rules  $(q, \bar{u}, q_1)$  in  $T_u$  with  $\bar{u}$  in  $\mathbb{Z}^d$  by “ $q \xrightarrow{\bar{u}} q_1$ ”, fork rules  $(q, q_1, q_2)$  in  $T_f$  by “ $q \rightarrow q_1 \wedge q_2$ ”, split rules  $(q, q_1, q_2)$  in  $T_s$  by “ $q \rightarrow q_1 + q_2$ ”, and full zero test rules  $(q, q_1)$  in  $T_z$  by “ $q \xrightarrow{\bar{0}} q_1$ ”.

### 3.1.2 Deduction Semantics

Given an  $ABVASS_{\bar{0}}$ , its semantics is defined by a deduction system over configurations  $(q, \bar{v})$  in  $Q \times \mathbb{N}^d$ :

$$\frac{q, \bar{v}}{q_1, \bar{v} + \bar{u}} \text{ unary}$$

where “+” denotes component-wise addition in  $\mathbb{N}^d$ , if  $q \xrightarrow{\bar{u}} q_1$  is a rule (and implicitly  $\bar{v} + \bar{u}$  has no negative component, i.e. is in  $\mathbb{N}^d$ ), and

$$\frac{q, \bar{v}}{q_1, \bar{v} \quad q_2, \bar{v}} \text{ fork} \quad \frac{q, \bar{v}_1 + \bar{v}_2}{q_1, \bar{v}_1 \quad q_2, \bar{v}_2} \text{ split} \quad \frac{q, \bar{0}}{q_1, \bar{0}} \text{ full-zero}$$

if  $q \rightarrow q_1 \wedge q_2$ ,  $q \rightarrow q_1 + q_2$ , and  $q \xrightarrow{\bar{0}} q_1$  are rules of the system, respectively, and “ $\bar{0}$ ” denotes the  $d$ -vector  $(0, \dots, 0)$  with zeroes on every coordinate. Such a deduction system can be employed either *top-down* or *bottom-up* depending on the decision problem at hand (as with tree automata); the top-down direction will correspond in a natural way to *proof search* in propositional linear logic, i.e. will correspond to the consequence to premises direction in the sequent calculus of Section 2.1.2.

### 3.1.3 Example

Let  $\mathcal{A}$  be an  $ABVASS_{\bar{0}}$  with five states  $(q_0, q_1, q_2, q_3, q_4)$ , of dimension 3, with six unary rules:

$$\begin{array}{lll} q_0 \xrightarrow{\langle 0, 1, 0 \rangle} q_1 & q_1 \xrightarrow{\langle 0, -1, 2 \rangle} q_1 & q_1 \xrightarrow{\langle 0, 0, 0 \rangle} q_2 \\ q_2 \xrightarrow{\langle 0, 1, -1 \rangle} q_2 & q_3 \xrightarrow{\langle 0, 0, 0 \rangle} q_0 & q_3 \xrightarrow{\langle -1, -2, 0 \rangle} q_4, \end{array}$$

and with one split rule  $q_2 \rightarrow q_3 + q_3$ . There are no fork rules and no full zero test rules in  $\mathcal{A}$ , and so it is a BVASS (see Section 3.3.2). A depiction of  $\mathcal{A}$  is in Figure 1, where we write  $c, d, d'$  for vector indices 1, 2, 3 (respectively), and specify unary rules in terms of increments and decrements.

From state  $q_0$  and with  $c, d, d'$  initialised to 4, 0, 0 (i.e., from a root node labelled by  $(q_0, \langle 4, 0, 0 \rangle)$ ),  $\mathcal{A}$  can reach  $q_2$  with  $d, d'$  having values 2, 0, perform the split rule by dividing  $c$  and  $d$  equally (i.e., branch to two nodes labelled by  $(q_3, \langle 2, 1, 0 \rangle)$ ), then in both threads reach  $q_2$  again with  $d, d'$  having values 4, 0, perform the split rule as before, and finally in all four threads reach  $q_4$  with  $c, d, d'$  having values 0, 0, 0 (i.e., have four leaf nodes, which are all labelled by  $(q_4, \bar{0})$ ).

Further reasoning can show that  $\mathcal{A}$  has a deduction tree whose root is labelled by  $(q_0, \langle m, 0, 0 \rangle)$  and with the state label at every leaf being  $q_4$  if and only if  $m \geq 4$ . In fact,  $\mathcal{A}$  is a slightly simplified version of the BVASS  $\mathcal{B}_2$  in Section 6.

## 3.2 Decision Problems

### 3.2.1 Reachability

Given an  $ABVASS_{\bar{0}}$   $\mathcal{A}$  and a finite set of states  $Q_\ell$ , we denote by a *root judgement* “ $\mathcal{A}, Q_\ell \triangleright q, \bar{v}$ ” the fact that there exists a deduction tree  $\mathcal{D}$  in  $\mathcal{A}$  with root label  $(q, \bar{v})$  and leaf labels in  $Q_\ell \times \{\bar{0}\}$ . We call  $\mathcal{D}$  a *reachability witness* for  $(q, \bar{v})$ . Given furthermore a state  $q_r$ , the *reachability problem* asks whether  $\mathcal{A}, Q_\ell \triangleright q_r, \bar{0}$ ; we call a reachability witness for  $(q_r, \bar{0})$  a *reachability witness*.

We will see in Section 4 that this reachability problem is equivalent to provability in LL; the problem is also related to games played over vectors of natural numbers, see the full paper. It is however undecidable:

**Fact 1.** *Reachability in  $ABVASS_{\bar{0}}$  is undecidable.*

*Proof.* Reachability is already undecidable in the more restricted model of AVASS, see Fact 2 below.  $\square$

### 3.2.2 Lossy Reachability

In order to obtain decidability, we must weaken the  $ABVASS_{\bar{0}}$  model or the decision problem. For the former, let us denote by  $\bar{e}_i$  the unit vector in  $\mathbb{N}^d$  with one on coordinate  $i$  and zero everywhere else. Then a *lossy*  $ABVASS_{\bar{0}}$  can be understood as featuring a rule  $q \xrightarrow{-\bar{e}_i} q$  for every  $q$  in  $Q$  and  $0 < i \leq d$ . We rather define it by extending its deduction system with

$$\frac{q, \bar{v}}{q, \bar{v} - \bar{e}_i} \text{ loss}$$

for every  $q$  in  $Q$  and  $0 < i \leq d$ . We write ‘ $\triangleright_\ell$ ’ for root judgements where losses can occur. In terms of proof search in linear logic, losses will correspond to structural weakening, which is the distinguishing feature of affine linear logic.

**Top-Down Coverability** An alternative way to see the reachability problem in lossy  $ABVASS_{\bar{0}}$  is to weaken the problem. Let us define a variant of  $ABVASS_{\bar{0}}$  that feature *full resets* instead of full zero tests: we denote in this case rules  $(q, q_1)$  in  $T_z$  by  $q \xrightarrow{\bar{0}} q_1$  and associate a different semantics:

$$\frac{q, \bar{v}}{q_1, \bar{0}} \text{ full-reset}$$

We call the resulting model  $ABVASS_r$ . Given an  $ABVASS_r$   $\mathcal{A}$ , a state  $q_r$ , and a finite set of states  $Q_\ell$ , the *top-down coverability* or *leaf coverability* problem asks whether there exists a deduction tree  $\mathcal{D}$  with root label  $(q_r, \bar{0})$  and such that, for each leaf, there exists some  $q_\ell$  in  $Q_\ell$  and some  $\bar{v}$  in  $\mathbb{N}^d$  such that the leaf label is  $(q_\ell, \bar{v})$ ; we then call  $\mathcal{D}$  a *coverability witness*.

The reachability problem for lossy  $ABVASS_{\bar{0}}$  is then equivalent to top-down coverability for  $ABVASS_r$ . Observe indeed that the unary, fork, and split rules are *monotone*: if  $\bar{v} \leq \bar{w}$  for the product ordering, i.e. if  $\bar{v}(i) \leq \bar{w}(i)$  for all  $0 < i \leq d$ , and a configuration  $(q, \bar{v})$  allows to apply a rule and result in some configurations  $(q_1, \bar{v}_1)$  and (possibly)  $(q_2, \bar{v}_2)$ , then  $(q, \bar{w})$  allows to apply the same rule and to obtain some  $(q_1, \bar{w}_1)$  and  $(q_2, \bar{w}_2)$  with  $\bar{v}_1 \leq \bar{w}_1$  and  $\bar{v}_2 \leq \bar{w}_2$ . This means that losses in an  $ABVASS_{\bar{0}}$  can be applied as late as possible, either right before a full zero test or at the leaves—which corresponds exactly to top-down coverability for  $ABVASS_r$ .

### 3.2.3 Expansive Reachability

In order to model structural contractions during proof search, it is natural to consider another variant of  $ABVASS_{\bar{0}}$  called *expansive*  $ABVASS_{\bar{0}}$  and equipped with the deduction rules

$$\frac{q, \bar{v} + \bar{e}_i}{q, \bar{v} + 2\bar{e}_i} \text{ expansion}$$

for every  $q$  in  $Q$  and  $0 < i \leq d$ . We write ‘ $\triangleright_e$ ’ for root judgments where expansions can occur. This is a restriction over  $\text{ABVASS}_0$  since expansions can be emulated through two unary rules  $q \xrightarrow{-e_i} q' \xrightarrow{2e_i} q$ . Expansive reachability is not quite dual to lossy reachability—we deal with *increasing reachability* in the full paper.

### 3.3 Restrictions

Note that  $\text{ABVASS}_0$  generalize *vector addition systems with states* (VASS), which are  $\text{ABVASS}_0$  with only unary rules. They also generalize two “branching” extensions of VASS, which have been defined in relation with propositional linear logic. Since these restrictions do not feature full zero tests, their lossy reachability problem is equivalent to their top-zero coverability problem.

#### 3.3.1 Alternating VASS

Alternating VASS were originally called “and-branching” counter machines by Lincoln et al. [14], and were introduced to prove the undecidability of propositional linear logic. Formally, an AVASS is an  $\text{ABVASS}_0$  which only features unary and fork rules, i.e. with  $T_s = T_z = \emptyset$ .

**Fact 2** (Lincoln et al. [14]). *Reachability in AVASS is undecidable.*

*Proof Idea.* By a reduction from the halting problem in Minsky machines: note that a zero test  $q \xrightarrow{c \stackrel{?}{=} 0} q'$  on a counter  $c$  can be emulated through a fork  $q \rightarrow q' \wedge q_c$ , where unary rules  $q_c \xrightarrow{-e_{c'}} q_c$  for all  $c' \neq c$  allow to empty the counters different from  $c$ , and a last unary rule  $q_c \xrightarrow{0} q_\ell$  to the single target state allows to check that  $c$  was indeed equal to zero.  $\square$

Alternating VASS do not allow to model LL proof search in full; Kanovich [9] identified the matching LL fragment, called the  $(!, \oplus)$ -Horn fragment.

The complexity of the other basic reachability problems on AVASS is known:

- motivated by the complexity of fragments of relevance logic, Urquhart [23] proved that expansive reachability is complete for Ackermannian time, and
- motivated by the complexity of vector addition games (see the full paper), Courtois and Schmitz [4] showed that lossy reachability is 2-EXPTIME-complete.

#### 3.3.2 Branching VASS

Inspired by the correspondences between the  $!$ -Horn fragment of linear logic and VASS unearthed by Kanovich [9], de Groote et al. [5] defined BVASS—which they originally dubbed “vector addition tree automata”—as a model of counter machines that matches MELL. Formally, a BVASS is an  $\text{ABVASS}_0$  with only unary and split rules, i.e. with  $T_f = T_z = \emptyset$ . This model turned out to be equivalent to independently defined models in linguistics [19] and protocol verification [25]; see [20] for a survey.

Whether BVASS reachability is decidable is an open problem, and is interreducible with MELL provability. Lazić [13] proved the best known lower bound to this day, which is 2-EXPSpace-hardness. Two related problems were shown to be 2-EXPTIME-complete by Demri et al. [6], namely increasing reachability (see the full paper) and boundedness.

#### 3.3.3 Alternating Branching VASS

Kopylov [10] defined a one-player vector game, which matches essentially the reachability problem in ABVASS, i.e. in  $\text{ABVASS}_0$

with  $T_z = \emptyset$ . The *elementary* fragment of ILL defined by Larchey-Wendling and Galmiche [12] is another counterpart to ABVASS.

While allowing full zero tests is helpful in the reduction from LL provability, they can be dispensed with at little expense. Let us first introduce some notation. If node  $n$  is an ancestor of a node  $n'$  in a deduction tree  $\mathcal{D}$ , and the labels of  $n$  and  $n'$  are the same, we write  $\mathcal{D}[n \leftarrow n']$  for the *shortening* of  $\mathcal{D}$  obtained by replacing the subtree of rule applications rooted at  $n$  by the one rooted at  $n'$ . Observe that, if  $\mathcal{D}$  is a reachability witness (resp. a coverability witness), then  $\mathcal{D}[n \leftarrow n']$  is also a reachability witness (resp. a coverability witness).

**Lemma 3.** *There is a logarithmic-space reduction from (lossy, resp. expansive)  $\text{ABVASS}_0$  reachability to (lossy, resp. expansive) ABVASS reachability, and a polynomial time Turing reduction that preserves the system dimension.*

*Proof.* Suppose  $\mathcal{A}$  is an  $\text{ABVASS}_0$  with set of states  $Q$  and dimension  $d$ .

For a logarithmic-space reduction, the key observation is that, if there exists a witness for an instance of (lossy, resp. expansive) reachability for  $\mathcal{A}$ , then by repeated shortenings, there must be one in which, along every vertical path, the number of occurrences of full zero tests is at most  $|Q| - 1$ .

It therefore suffices to decide the problem for an  $\text{ABVASS } \mathcal{A}^\dagger$  whose set of states is  $\{1, \dots, |Q|\} \times Q$ , whose dimension is  $|Q| \cdot d$ , and which simulates  $\mathcal{A}$  up to  $|Q| - 1$  full zero tests along any vertical path. In any state  $(i, q)$ ,  $\mathcal{A}^\dagger$  behaves like  $\mathcal{A}$  in state  $q$ , but using the  $i$ th  $d$ -tuple of its vector components. To simulate a full zero test  $q \xrightarrow{\stackrel{?}{=} 0} q'$  in  $\mathcal{A}$ ,  $\mathcal{A}^\dagger$  changes state from  $(i, q)$  to  $(i + 1, q)$ , postponing the check that the  $i$ th  $d$ -tuple of vector components are zero until the leaves.

For a reduction that preserves  $d$ , we define the set of *root states* relative to a subset  $X$  of  $Q$  by

$$\text{Root}_{\mathcal{A}}(X) \stackrel{\text{def}}{=} \{q \in Q \mid \mathcal{A}, X \triangleright q, \bar{0}\} \quad (1)$$

as the set of states  $q$  such that there exists a deduction in  $\mathcal{A}$  with root label  $(q, \bar{0})$  and leaf labels in  $X \times \{\bar{0}\}$ . The (lossy, resp. expansive) reachability problem for  $\langle \mathcal{A}, q_r, Q_\ell \rangle$  then reduces to checking whether  $q_r$  belongs to  $\text{Root}_{\mathcal{A}}(Q_\ell)$ .

Writing  $\mathcal{A}'$  for the corresponding ABVASS, we can compute  $\text{Root}_{\mathcal{A}'}(X)$  using  $|Q|$  calls to an oracle for (lossy, resp. expansive) ABVASS reachability. Moreover, since  $\text{Root}_{\mathcal{A}'}(X) \supseteq X$  is monotone, we can use a least fixed point computation that discovers root states according to the number of full zero tests along the branches of their reachability witnesses:

$$\text{Root}_{\mathcal{A}}(Q_\ell) = \mu X. \text{Root}_{\mathcal{A}'}(Q_\ell) \cup \text{Root}_{\mathcal{A}'}(X \cup T_z^{-1}(X)). \quad (2)$$

This computation converges after at most  $|Q|$  steps, and therefore works in polynomial time relative to the same oracle.  $\square$

## 3.4 Computational Complexity

### 3.4.1 Non-Elementary Complexity Classes

We will use in this paper two complexity classes [see 21]:

$$\text{TOWER} \stackrel{\text{def}}{=} \bigcup_{e \in \text{FELEM}} \text{DTIME}(\text{tower}(e(n))) \quad (3)$$

is the class of problems that can be solved with a deterministic Turing machine in time tower of some elementary function  $e$  of the input, where  $\text{tower}(0) \stackrel{\text{def}}{=} 1$  and  $\text{tower}(n + 1) \stackrel{\text{def}}{=} 2^{\text{tower}(n)}$  defines towers of exponentials. Similarly,

$$\text{ACKERMANN} \stackrel{\text{def}}{=} \bigcup_{p \in \text{FPR}} \text{DTIME}(\text{Ack}(p(n))) \quad (4)$$

is the class of problems solvable in time  $\text{Ack}$  of some primitive recursive function  $p$  of the input size, where “Ack” denotes the Ackermann function—any standard definition of Ack yields the same complexity class [21].

Completeness for TOWER is understood relative to many-one elementary reductions, and completeness for ACKERMANN relative to many-one primitive-recursive reductions.

### 3.4.2 ABVASS<sub>0</sub> Complexity

For a set  $T_u$  of unary rules, we write  $\max^-(T_u)$  (resp.  $\max^+(T_u)$ ) for the largest absolute value of any negative (resp. positive) integer in a vector in  $T_u$ , and  $\max(T_u)$  for their overall maximum. We assume a binary encoding of the vectors in unary rules, thus  $\max(T_u)$  might be exponential in the size of the ABVASS<sub>0</sub>. We can however reduce to *ordinary* ABVASS<sub>0</sub>, i.e. ABVASS<sub>0</sub> with  $\bar{u} = \bar{e}_i$  or  $\bar{u} = -\bar{e}_i$  for some  $0 < i \leq d$  whenever  $q \xrightarrow{\bar{u}} q_1$  is a unary rule:

**Lemma 4.** *There is a logarithmic space reduction from reachability in (lossy, resp. expansive) ABVASS<sub>0</sub> to reachability in (lossy, resp. expansive) ordinary ABVASS<sub>0</sub>.*

*Proof Idea.* The idea is to encode each of the  $d$  coordinates of the original ABVASS<sub>0</sub> into  $\lceil \log(\max(T_u) + 1) \rceil$  coordinates, and each unary rule to apply a binary encoding of  $\bar{u}$  to those new coordinates; see for instance [20] where this construction is detailed for BVASS. The expansive case requires to first explicitly encode expansions as unary rules.  $\square$

**Lossy Case** One of the main results of this paper is the following:

**Theorem 5.** *Reachability in lossy BVASS and lossy ABVASS<sub>0</sub> is TOWER-complete.*

*Proof.* The upper bound is proved in Section 5. We present the hardness proof in detail in Section 6.  $\square$

Note that Theorem 5 entails an improvement for BVASS reachability over the 2-EXSPACE lower bound of Lazić [13].

**Expansive Case** Regarding expansive ABVASS<sub>0</sub>, we can adapt the proofs of Urquhart [23] for expansive AVASS and the relevance calculus LR+ to show:

**Theorem 6.** *Reachability in expansive AVASS and expansive ABVASS<sub>0</sub> is ACKERMANN-complete.*

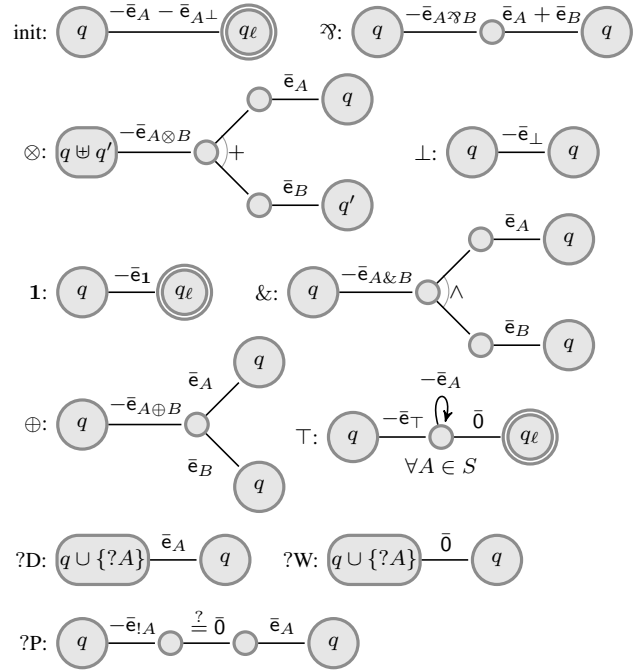
*Proof.* The lower bound is due to Urquhart [23], who proved hardness of expansive AVASS reachability by a direct reduction from the halting problem of Minsky machines with counter values bounded by the Ackermann function. The upper bound can be proved following essentially the same arguments as Urquhart’s for LR+, using length function theorems for Dickson’s Lemma [see e.g. 8]. See the full paper for a proof.  $\square$

Theorem 6 allows to derive the same ACKERMANN bounds for provability in MALLC and LLC, see the full paper.

## 4. Relationships Between LL and ABVASS<sub>0</sub>

### 4.1 From LL to ABVASS<sub>0</sub>

We present here a direct reduction from LL provability to ABVASS<sub>0</sub> reachability, which relies on the subformula property of the sequent calculus. Consider for this a formula  $F$  of linear logic; we know that, if  $\vdash F$  is provable, then it has a cut-free proof tree, where all the nodes are labeled by multisets of subformulae of  $F$ . More precisely, a sequent  $\vdash \Gamma$  appearing in such a proof can be written as  $\vdash ?\Psi, \Delta$  where the formulae in  $\Delta$  are *not* guarded by why-nots;



**Figure 2.** The rules of  $\mathcal{A}_F$ ;  $q$  and  $q'$  are subsets of  $S_?$ .

writing  $S_?$  for the  $?$ -guarded subformulae of  $F$  and  $S$  for its remaining subformulae, it means that  $?\Psi$  is a multiset over  $S_?$  and  $\Delta$  a multiset over  $S$ . Let us denote by “ $\vdash_F$ ” the provability relation restricted to subformulae of  $F$ ; then  $\vdash F$  if and only if  $\vdash_F F$ .

We define an ABVASS<sub>0</sub>  $\mathcal{A}_F$  that maintains an encoding of a sequent  $\vdash_F ?\Psi, \Delta$  as the configuration  $(\sigma(?\Psi), \Delta)$  over  $2^{S_?} \times \mathbb{N}^S$  where, for any multiset  $m$  over some set  $E$ ,

$$\sigma(m) \stackrel{\text{def}}{=} \{e \in E \mid m(e) > 0\} \quad (5)$$

denotes the *support* of the multiset. The ABVASS<sub>0</sub>  $\mathcal{A}_F$  includes  $2^{S_?}$ , a distinguished root state  $q_r$ , and a distinguished leaf state  $q_\ell$  as part of its state space; it works in dimension  $|S|$  and its rules and intermediate states are depicted in Figure 2. It encodes the sequent calculus of Section 2.1.2 in a straightforward way; the rules maintain the following invariant, which can be checked by induction on the height of deduction trees and proof trees:

$$\mathcal{A}_F, \{q_\ell\} \triangleright \sigma(?\Psi), \Delta \quad \text{iff} \quad \vdash_F ?\Psi, \Delta. \quad (6)$$

Two cases arise at the root of deductions in  $\mathcal{A}_F$ : either  $F = ?F'$ , and we add a rule  $q_r \xrightarrow{\bar{0}} \{?F'\}$  to the rules depicted in Figure 2, or  $F$  is not guarded by a why-not, and we add a rule  $q_r \xrightarrow{\bar{e}_F} \emptyset$ . Then, by (6),  $\mathcal{A}_F, \{q_\ell\} \triangleright q_r, \bar{0}$  if and only if  $\vdash_F F$ .

It is worth noting that the logical contraction rule (?C) is handled implicitly by the use of supports, and that, for each  $q \uplus q' \subseteq S_?$ ,  $\mathcal{A}_F$  features a single split rule, for ( $\otimes$ ), a single fork rule, for ( $\&x$ ), and a single full zero test rule, for (?P). This means in particular that MELL provability can be reduced to BVASS<sub>0</sub> reachability—and thus by the proof of Lemma 3, to BVASS reachability. Also observe that structural weakening (W) and structural contraction (C) can be handled respectively by losses and expansions in  $\mathcal{A}_F$ . We conclude:

**Proposition 7.** *There are polynomial space reductions:*

1. *from (affine, resp. contractive) LL provability to (lossy, resp. expansive) ABVASS<sub>0</sub> reachability,*

2. from (affine, resp. contractive) MELL provability to (lossy, resp. expansive) BVASS<sub>0</sub> reachability.

Our reductions incur an exponential blow-up in the number of states—however, as we will see with our complexity upper bounds, this is not an issue, because the main source of complexity in ABVASS<sub>0</sub> is, by far, the dimension of the system, which is here linear in  $|F|$ . We provide similar reductions for the intuitionistic cases in the full paper, where the proof for an intuitionistic version of (6) is also provided in greater detail.

## 4.2 From ABVASS<sub>0</sub> to LL

In order to exhibit a reduction from ABVASS<sub>0</sub> reachability to LL provability, we extend a similar reduction proved by Lincoln, Mitchell, Scedrov, and Shankar [14] in the case of AVASS (also employed by Urquhart [23]). The general idea is to encode ABVASS<sub>0</sub> configurations as sequents and ABVASS<sub>0</sub> deductions as proofs in LL extended with a *theory*, where encoded ABVASS<sub>0</sub> rules are provided as an additional set of non-logical axioms.

### 4.2.1 Linear Logic with a Theory

In the framework of Lincoln et al., a theory  $T$  is a finite set of axioms  $C, p_1^\perp, \dots, p_m^\perp$  where  $C$  is a MALL formula and each  $p_i$  is an atomic proposition. Proofs in LL+ $T$  can employ two new rules

$$\frac{}{\vdash C, p_1^\perp, \dots, p_m^\perp} T \quad \frac{\vdash C, p_1^\perp, \dots, p_m^\perp \quad \vdash C^\perp, \Delta}{\vdash p_1^\perp, \dots, p_m^\perp, \Delta} \text{ directed cut}$$

where  $C, p_1^\perp, \dots, p_m^\perp$  belongs to  $T$ .

A proof in LL+ $T$  is directed if all its cuts are *directed cuts*. By adapting the LL cut-elimination proof, Lincoln et al. show:

**Fact 8** ([14]). *If there is a proof of  $\vdash \Gamma$  in LL+ $T$ , then there is a directed proof of  $\vdash \Gamma$  in LL+ $T$ .*

The axioms of a theory  $T$  can be translated in pure LL by

$$\ulcorner C, p_1^\perp, \dots, p_m^\perp \urcorner \stackrel{\text{def}}{=} C^\perp \otimes p_1 \otimes \dots \otimes p_m. \quad (7)$$

**Fact 9** ([14]). *For any finite set of axioms  $T$ ,  $\vdash \Gamma$  is provable in LL+ $T$  if and only if  $\ulcorner T \urcorner, \Gamma$  is provable in LL.*

### 4.2.2 Encoding ABVASS<sub>0</sub>

Given an ABVASS  $\mathcal{A} = \langle Q, d, T_u, T_f, T_s, \emptyset \rangle$ , a configuration  $(q, \bar{v})$  in  $Q \times \mathbb{N}^d$  is encoded as the sequent

$$\theta(q, \bar{v}) \stackrel{\text{def}}{=} \vdash q^\perp, (e_1^\perp)^{\bar{v}(1)}, \dots, (e_d^\perp)^{\bar{v}(d)} \quad (8)$$

where  $Q \uplus \{e_i \mid i = 1, \dots, d\}$  is included in the set of atomic propositions and  $A^n$  stands for the formula  $A$  repeated  $n$  times.

By Lemma 4 we assume  $\mathcal{A}$  to be in ordinary form. We construct from the rules of  $\mathcal{A}$  a theory  $T$  consisting of sequents of form  $\vdash q^\perp, c_1^\perp, \dots, c_m^\perp, C$  with  $q$  in  $Q$  the originating state,  $c_j$  in  $\{e_i \mid 0 < i \leq d\}$ , and  $C$  a MALL formula containing the destination state(s) positively. Here are the axioms corresponding to each type of rule:

$$\begin{array}{ll} q \xrightarrow{\bar{e}_i} q_1 & q^\perp, q_1 \otimes e_i \\ q \xrightarrow{-\bar{e}_i} q_1 & q^\perp, e_i^\perp, q_1 \\ q \rightarrow q_1 \wedge q_2 & q^\perp, q_1 \oplus q_2 \\ q \rightarrow q_1 + q_2 & q^\perp, q_1 \wp q_2 \end{array}$$

By Lemma 3, we do not need to consider the case of full zero tests. Here is nevertheless how they could be encoded, provided we slightly extended the reduction of LL+ $T$  to LL in Fact 9 to allow exponentials in  $T$ :

$$q \xrightarrow{\bar{0}} q_1 \quad q^\perp, !q_1$$

**Claim 10.1.** For all  $(q, \bar{v})$  in  $Q \times \mathbb{N}^d$ ,  $\mathcal{A}, Q_\ell \triangleright q, \bar{v}$  if and only if  $\vdash \theta(q, \bar{v}), ?Q_\ell$  in LL+ $T$ .

*Proof.* The AVASS case is proved by Lincoln et al. [14, Lemmata 3.5 and 3.6] by induction on the height of deduction trees in  $\mathcal{A}$  and the number of directed cuts in a directed proof in LL+ $T$  (with minor adaptations for  $?Q_\ell$ ). Thus, we only need to prove that split rules preserve this statement.<sup>2</sup>

Assume for the direct implication that  $\mathcal{A}, Q_\ell \triangleright q, \bar{v}$  as the result of a split rule  $q \rightarrow q_1 + q_2$ , thus  $\bar{v} = \bar{v}_1 + \bar{v}_2$  and  $\mathcal{A}, Q_\ell \triangleright q_1, \bar{v}_1$  and  $\mathcal{A}, Q_\ell \triangleright q_2, \bar{v}_2$ . By induction hypothesis,  $\vdash \theta(q_1, \bar{v}_1), ?Q_\ell$  and  $\vdash \theta(q_2, \bar{v}_2), ?Q_\ell$ , and we can prove

$$\vdash q_1^\perp \otimes q_2^\perp, (c_1^\perp)^{\bar{v}_1(1)+\bar{v}_2(1)}, \dots, (c_d^\perp)^{\bar{v}_1(d)+\bar{v}_2(d)}, ?Q_\ell, ?Q_\ell \quad (9)$$

using  $(\otimes)$ , and after  $|Q_\ell|$  logical contractions and a directed cut with  $\vdash q^\perp, q_1 \wp q_2$ , we obtain  $\vdash \theta(q, \bar{v}), ?Q_\ell$  as desired.

Conversely, assume that the last applied directed cut has

$$\vdash q_1^\perp \otimes q_2^\perp, (c_1^\perp)^{\bar{v}(1)}, \dots, (c_d^\perp)^{\bar{v}(d)}, ?Q_\ell \quad (10)$$

and  $\vdash q^\perp, q_1 \wp q_2$  as premises. The only rules that allow to prove (10) are (?D), (?C) or (?W) applied to some  $q_\ell$  in  $Q_\ell$ , and  $(\otimes)$ . Logical contractions are irrelevant to the claim, and wlog. we can apply derelictions above  $(\otimes)$ , thus we know that (10) is the result of  $(\otimes)$  followed by a series of (?W). Hence  $\vdash \theta(q_1, \bar{v}_1), ?Q_1$  and  $\vdash \theta(q_2, \bar{v}_2), ?Q_2$  with  $\bar{v} = \bar{v}_1 + \bar{v}_2$  and  $Q_\ell \supseteq Q_1 \cup Q_2$ . By induction hypothesis,  $\mathcal{A}, Q_1 \triangleright q_1, \bar{v}_1$  and  $\mathcal{A}, Q_2 \triangleright q_2, \bar{v}_2$ . Because  $Q_1 \subseteq Q_\ell$  and  $Q_2 \subseteq Q_\ell$  this entails  $\mathcal{A}, Q_\ell \triangleright q_1, \bar{v}_1$  and  $\mathcal{A}, Q_\ell \triangleright q_2, \bar{v}_2$ , from which a split allows to derive  $\mathcal{A}, Q_\ell \triangleright q, \bar{v}$  as desired.  $\square$

**Proposition 10.** *There are logarithmic space reductions*

1. from ABVASS<sub>0</sub> reachability to LL provability and
2. from BVASS<sub>0</sub> reachability to MELL provability.

*Proof.* By Lemma 3 we can eliminate full zero tests. For 1, by Claim 10.1 and Fact 9,  $\mathcal{A}, Q_\ell \triangleright q_r, \bar{0}$  if and only if  $\vdash q_r^\perp, ?Q_\ell, ?\ulcorner T \urcorner$ . Regarding 2, simply observe that additive connectives are only used for the encoding of fork rules.  $\square$

### 4.2.3 Affine Case

Adapting the proof of Proposition 10 to the affine case is relatively straightforward. For starters, Fact 8 also holds for LLW+ $T$  using the cut elimination procedure for LLW, and allowing structural weakenings does not influence the proof of Fact 9 in [14, Lemmata 3.2 and 3.3]. We show:

**Proposition 11.** *There are logarithmic space reductions*

1. from ABVASS<sub>0</sub> lossy reachability to LLW provability and
2. from BVASS<sub>0</sub> lossy reachability to MELLW provability.

This relies on an extension of Claim 10.1:

**Claim 11.1.** For all  $(q, \bar{v})$  in  $Q \times \mathbb{N}^d$ ,  $\mathcal{A}, Q_\ell \triangleright_\ell q, \bar{v}$  with lossy semantics if and only if  $\vdash \theta(q, \bar{v}), ?Q_\ell$  in LLW+ $T$ .

### 4.2.4 Contractive Case

Again, Fact 8 is straightforward to adapt to LLC+ $T$  using cut elimination. Fact 9 can be strengthened to avoid exponentials in the contractive case; see the full paper for a proof:

**Lemma 12.** *For a finite set of axioms  $T$ ,  $\vdash \Gamma$  is provable in LLC+ $T$  if and only if  $\vdash \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \Gamma$  is provable in LLC.*

<sup>2</sup>de Groote et al. [5] show how to handle split rules in IMELL, but they do not rely on the LL+ $T$  framework, which motivates considering this case.

*Proof.* For the direct implication, we consider a directed proof of  $\vdash_{\text{LLC}+T} \Gamma$ . By induction on the number of directed cuts, we build an LLC proof of  $\vdash_{\text{LLC}} \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \Gamma$ . For the base case, an LLC+T proof without directed cuts is also an LLC proof, thus  $\vdash_{\text{LLC}+T} \top, \Gamma$  using the ( $\top$ ) rule, and  $\vdash \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \Gamma$  by  $|T|$  applications of ( $\oplus$ ). For the induction step, consider a directed cut of an axiom  $t = C, p_1^\perp, \dots, p_m^\perp$  in  $T$  with  $\vdash_{\text{LLC}+T} C^\perp, \Delta$ . We have  $\vdash_{\text{LLC}} C, C^\perp$  and  $\vdash_{\text{LLC}} p_i, p_i^\perp$  for all  $0 < i \leq m$  by the (init) rule, and  $m + 1$  applications of ( $\otimes$ ) yield  $\vdash_{\text{LLC}} t, \ulcorner t \urcorner$ . By induction hypothesis  $\vdash_{\text{LLC}} \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, C^\perp, \Delta$ , thus a (normal) cut yields  $\vdash_{\text{LLC}} \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \ulcorner t \urcorner, p_1^\perp, \dots, p_m^\perp, \Delta$ . Using  $|T|$  applications of ( $\oplus$ ) allows to prove  $\vdash_{\text{LLC}} \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, p_1^\perp, \dots, p_m^\perp, \Delta$  and a structural contraction yields the desired LLC proof.

For the converse implication, if  $\vdash_{\text{LLC}} \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \Gamma$ , then  $\vdash_{\text{LLC}+T} \top \oplus \bigoplus_{t \in T} \ulcorner t \urcorner, \Gamma$ . Then  $\vdash_{\text{LLC}+T} \mathbf{1}$ , and for each axiom  $t = C, p_1^\perp, \dots, p_m^\perp$  in  $T$ , we can prove  $\vdash_{\text{LLC}+T} C \wp p_1^\perp \wp \dots \wp p_m^\perp$  by  $m$  applications of ( $\wp$ ) from  $\vdash_{\text{LLC}+T} \mathbf{1}$ , i.e.  $\vdash_{\text{LLC}+T} \ulcorner t \urcorner^\perp$ . Thus  $|T|$  applications of ( $\&$ ) yield  $\vdash_{\text{LLC}+T} \mathbf{1} \& \&_{t \in T} \ulcorner t \urcorner^\perp$ , and a (normal) cut shows  $\vdash_{\text{LLC}+T} \Gamma$ .  $\square$

Without loss of generality, we can assume that  $Q_\ell = \{q_\ell\}$  for a state  $q_\ell$  with no applicable rule in  $\mathcal{A}$ . We extend Claim 10.1 and Proposition 10 to the contractive case; see the full paper:

*Claim 13.1.* For all  $(q, \bar{v})$  in  $Q \times \mathbb{N}^d$ ,  $\mathcal{A}, \{q_\ell\} \triangleright_e q, \bar{v}$  using expansive semantics if and only if  $\vdash \theta(q, \bar{v}), q_\ell^s$  in LLC+T for some  $s > 0$ .

**Proposition 13.** *There is a logarithmic space reduction from ABVASS $_{\bar{0}}$  expansive reachability to MALLC provability.*

## 5. TOWER Upper Bounds

To show that the reachability problem for lossy ABVASS $_{\bar{0}}$  is in TOWER, we establish by induction over the dimension  $d$  a bound on the height of minimal reachability witnesses, following in this the reasoning used by Rackoff [18] to show that the coverability problem for VASS is in EXPSpace. The main new idea here is that, where there is freedom to choose how values of vector components are distributed when performing split rules top-down (see Section 3.1), splitting them equally (or with the difference of 1) allows sufficient lower bounds to be established along vertical paths in deduction trees for the inductive argument to go through. Since the bounds we obtain on the heights of smallest witnessing deduction trees are exponentiated at every inductive step (rather than multiplied as in Rackoff's proof), the resulting complexity upper bound involves a tower of exponentials, but will be shown broadly optimal in Section 6.

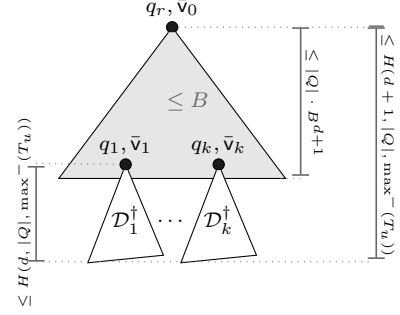
The following lemma in fact addresses the equivalent top-down coverability problem (see Section 3.2.2), and considers systems without full resets thanks to Lemma 3. We first define some terminology. We say that a deduction tree is:

- $(q_r, \bar{v}_0)$ -rooted iff that is the label of its root;
- $Q_\ell$ -leaf-covering iff, for every leaf label  $(q, \bar{v})$ , we have  $q \in Q_\ell$ ;
- of height  $h$  iff that is the maximum number of edges, i.e. the maximum number of rule applications, along any path from the root to a leaf.

For integers  $d, m \geq 0$  and  $s \geq 1$ , we define a natural number  $H(d, s, m)$  recursively:

$$H(0, s, m) \stackrel{\text{def}}{=} s, \quad (11)$$

$$H(d+1, s, m) \stackrel{\text{def}}{=} s(m \cdot 2^{H(d, s, m)})^{d+1} + H(d, s, m). \quad (12)$$



**Figure 3.** Induction step in the proof of Lemma 14.

**Lemma 14.** *If an ABVASS  $\mathcal{A} = \langle Q, d, T_u, T_f, T_s, \emptyset \rangle$  has a  $(q_r, \bar{v}_0)$ -rooted  $Q_\ell$ -leaf-covering deduction tree, then it has such a deduction tree of height at most  $H(d, |Q|, \max^-(T_u))$ .*

*Proof.* We use induction on the dimension  $d$ .

If  $\mathcal{A}$  is 0-dimensional, then the labels in its deduction trees are states only. Starting with a deduction tree whose root label is  $q_r$  and whose every leaf label is in  $Q_\ell$ , we obtain by repeated shortenings a deduction tree in which labels along every branch are mutually distinct, with height at most  $|Q| - 1$ .

Suppose that  $\mathcal{A} = \langle Q, d+1, T_u, T_f, T_s, \emptyset \rangle$ , and  $\mathcal{D}$  is a  $(q_r, \bar{v}_0)$ -rooted  $Q_\ell$ -leaf-covering deduction tree. Let

$$B \stackrel{\text{def}}{=} 2^{H(d, |Q|, \max^-(T_u))} \cdot \max^-(T_u), \quad (13)$$

and let  $\{n_1, \dots, n_k\}$  be the set of all nodes of  $\mathcal{D}$  such that, for all  $i$ , we have:

- all vector components in labels of ancestors of  $n_i$  are smaller than  $B$ ;
- for some  $0 < j_i \leq d+1$ , we have  $\bar{v}_i(j_i) \geq B$ , where the label of  $n_i$  is  $(q_i, \bar{v}_i)$ .

By repeated shortenings, we can assume that the length (i.e., the number of edges) of every path in  $\mathcal{D}$ , which is from the root either to some  $n_i$  or to a leaf with no  $n_i$  ancestor, is at most  $|Q| \cdot B^{d+1}$ , the number of possible labels with all vector components smaller than  $B$ .

In the remainder of the argument, we apply the induction hypothesis below each of the nodes  $n_i$ . More precisely, let  $\mathcal{A}_i$  denote the  $d$ -dimensional ABVASS obtained from  $\mathcal{A}$  by projecting onto vector indices  $\{1, \dots, d+1\} \setminus \{j_i\}$ . (The only change is in the set of unary rules.) From the subtree of  $\mathcal{D}$  rooted at  $n_i$ , we know that  $\mathcal{A}_i$  has a  $(q_i, \bar{v}_i(-j_i))$ -rooted  $Q_\ell$ -leaf-covering deduction tree. (Here  $\bar{w}(-j)$  is the projection of  $\bar{w}$  to all indices except  $j$ .) Let  $\mathcal{D}_i$  be such a deduction tree, which we can choose of height at most  $H(d, |Q|, \max^-(T_u))$  by induction hypothesis.

Now, to turn  $\mathcal{D}_i$  into a  $(q_i, \bar{v}_i)$ -rooted deduction tree  $\mathcal{D}_i^\dagger$  of  $\mathcal{A}$ , we have to do two things:

1. For every application of a unary rule  $q \xrightarrow{\bar{u}} q'$  in  $\mathcal{D}_i$ , decide which unary rule  $q \xrightarrow{\bar{u}'} q'$  of  $\mathcal{A}$  such that  $\bar{u} = \bar{u}'(-j_i)$  to apply: we do that arbitrarily.
2. For every application of a split rule  $q \rightarrow q' + q''$  in  $\mathcal{D}_i$ , decide how to split the vector component  $x$  with index  $j_i$ : we do that by balancing, i.e. picking the corresponding components  $x_1$  and  $x_2$  of the two child vectors so that  $|x_1 - x_2| \leq 1$ .

We claim that  $\mathcal{D}_i^\dagger$  thus obtained is indeed a  $(q_i, \bar{v}_i)$ -rooted  $Q_\ell$ -leaf-covering deduction tree of  $\mathcal{A}$ . Since the node labels in  $\mathcal{D}_i^\dagger$  differ from those in  $\mathcal{D}_i$  only by the extra  $j_i$ th components, it suffices



to show that all the latter are non-negative. In fact, at the root of  $\mathcal{D}_i^\dagger$ , we have  $\bar{v}_i(j_i) \geq B$ , and it follows by a straightforward induction that, for every node  $n$  in  $\mathcal{D}_i^\dagger$  whose distance from the root is  $h$  (which is at most  $H(d, |Q|, \max^-(T_u))$ ), its vector label  $\bar{w}$  satisfies

$$\bar{w}(j_i) \geq 2^{H(d, |Q|, \max^-(T_u)) - h} \cdot \max^-(T_u). \quad (14)$$

It remains to observe that, by replacing for each  $0 < i \leq k$ , the subtree of  $\mathcal{D}$  rooted at  $n_i$  by  $\mathcal{D}_i^\dagger$ , the height of the resulting deduction tree (see Figure 3 for a depiction) is at most

$$|Q| \cdot B^{d+1} + H(d, |Q|, \max^-(T_u)) = H(d+1, |Q|, \max^-(T_u)),$$

thereby establishing the lemma.  $\square$

The following auxiliary function and proposition will be useful for deriving the complexity upper bounds. Let

$$H'(d, s, m) \stackrel{\text{def}}{=} 4(d+1)(s+m+1)H(d, s, m). \quad (15)$$

We show in the full paper that:

**Proposition 15.** *For all  $d, m \geq 0$  and  $s \geq 1$ , we have:*

$$H'(d+1, s, m) \leq 2^{H'(d, s, m)}.$$

We are now in a position to establish the membership in TOWER. More precisely, since the height of the tower of exponentials in the bounds we obtained is equal to the system dimension, the problem with the dimension  $d$  fixed will be in  $d$ -EXPTIME.

**Theorem 16.** *Reachability for lossy ABVASS $_{\bar{v}_0}$  is in TOWER. For every fixed dimension  $d$ , it is in PTIME if  $d = 0$ , and in  $d$ -EXPTIME if  $d \geq 1$ .*

*Proof.* By Lemma 3, it suffices to consider an ABVASS. We argue in terms of the top-down coverability problem (see Section 3.2.2): given an ABVASS  $\mathcal{A} = \langle Q, d, T_u, T_f, T_s, \emptyset \rangle$ , a state  $q_r$  and a set of states  $Q_\ell$ , to decide whether  $\mathcal{A}$  has a  $(q_r, \bar{v}_0)$ -rooted  $Q_\ell$ -leaf-covering deduction tree.

By Lemma 14, if  $\mathcal{A}$  has such a deduction tree, then it has one of height at most  $H(d, |Q|, \max^-(T_u))$ . Observing that, in such a deduction tree, all vector components are bounded by

$$(\max^+(T_u) + 1) \cdot H(d, |Q|, \max^-(T_u)),$$

we conclude that it can be guessed and checked in

$$O((d+1) \cdot \log((\max^+(T_u) + 1) \cdot H'(d, |Q|, \max^-(T_u))))$$

space by an alternating algorithm which manipulates at most three configurations of  $\mathcal{A}$  at a time.

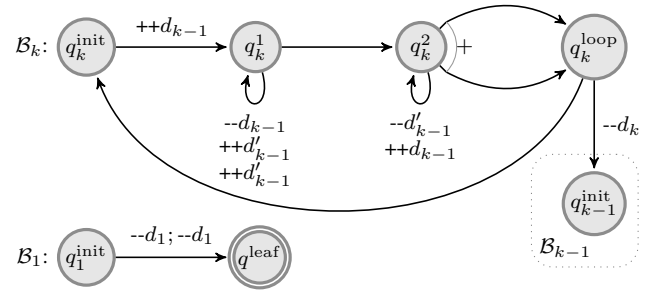
The memberships in the statement (for ABVASS) follow from the fact that  $H'(0, |Q|, \max^-(T_u))$  is polynomial, by Proposition 15, and since  $\text{ALOGSPACE} = \text{PTIME}$ ,  $\text{APSPACE} = \text{EXPTIME}$ , and  $(d-1)\text{-AEXPSPACE} = d\text{-EXPTIME}$ .  $\square$

By Proposition 7, this shows:

**Corollary 17.** *LLW provability is in TOWER.*

## 6. TOWER Lower Bounds

The rough pattern of our hardness proof resembles those by e.g. Urquhart [23], where a fast-growing function is computed weakly, then its result is used to allocate space for simulating a universal machine, and finally the inverse of the function is computed weakly for checking purposes. Indeed, we simulate Minsky machines whose counters are tower-bounded, but the novelty here is in the inverse computations. Specifically, for each Minsky counter  $c$ , we maintain its dual  $\hat{c}$  and simulate each zero test on  $c$  by a split rule that launches a thread to check that  $\hat{c}$  has the maximum value.



**Figure 4.** Defining  $\mathcal{B}_k$  for  $k > 1$  (above), and  $\mathcal{B}_1$  (below).

Recalling that such rules split all values non-deterministically, we must construct the simulating system carefully so that such non-determinism cannot result in erroneous behaviours.

The auxiliary threads check that a counter is at least  $\text{tower}(k)$  by seeking to apply split rules at least  $\text{tower}(k-1)$  times along every branch. The difficulty here is, similarly, how to count up to  $\text{tower}(k-1)$  or more in a manner which is robust with respect to the non-determinism of the split rules.

A hierarchy of BVASS for the latter purpose is given in Figure 4—recall the depicting conventions in Section 3.1.3. Thus, after the unary rule from  $q_k^{\text{loop}}$  that decrements  $d_k$ , we have that  $\mathcal{B}_k$  behaves like  $\mathcal{B}_{k-1}$  from state  $q_{k-1}^{\text{init}}$ .

**Lemma 18.** *For every  $k \geq 1$  and vector of naturals  $\bar{v}_0$  such that  $\bar{v}_0(d_i) = \bar{v}_0(d'_i) = 0$  for all  $i < k$ , we have that  $\mathcal{B}_k$  has a  $(q_k^{\text{init}}, \bar{v}_0)$ -rooted  $\{q^{\text{leaf}}\}$ -leaf-covering deduction tree if and only if  $\bar{v}_0(d_k) \geq \text{tower}(k)$ .*

*Proof.* We proceed by induction on  $k$ , where the base case  $k = 1$  is immediate, so let us consider  $k > 1$  and  $\bar{v}_0$  such that  $\bar{v}_0(d_i) = \bar{v}_0(d'_i) = 0$  for all  $i < k$ .

If  $\bar{v}_0(d_k) \geq \text{tower}(k)$ , we observe that  $\mathcal{B}_k$  can proceed from  $(q_k^{\text{init}}, \bar{v}_0)$  as follows:

- each loop at  $q_k^1$  empties  $d_{k-1}$ , i.e. doubles  $d_{k-1}$  and transfers it to  $d'_{k-1}$ ;
- each loop at  $q_k^2$  empties  $d'_{k-1}$ , i.e. transfers  $d'_{k-1}$  to  $d_{k-1}$ ;
- each split from  $q_k^2$  divides  $d_{k-1}$  into two equal values, and divides  $d_k$  into two values that differ by at most 1.

In any deduction tree thus obtained, at every node which is the  $h$ th node with state label  $q_k^{\text{loop}}$  from the root, and whose vector label is  $\bar{w}$ , we have:

$$\bar{w}(d_{k-1}) = h, \quad \bar{w}(d'_{k-1}) = 0, \quad \bar{w}(d_k) \geq 2^{\text{tower}(k-1) - h}. \quad (16)$$

Hence, by returning control to  $q_k^{\text{init}}$  as long as the value of  $d_k$  is at least 2,  $\mathcal{B}_k$  can reach along every vertical path a node with state label  $q_k^{\text{loop}}$  at which the values of  $d_{k-1}$  and  $d_k$  are equal to  $\text{tower}(k-1)$  and at least 1 (respectively). To complete the deduction tree to be  $\{q^{\text{leaf}}\}$ -leaf-covering, from every such node we let  $\mathcal{B}_k$  decrement  $d_k$  and apply the induction hypothesis.

The interesting direction remains, so suppose  $\mathcal{D}$  is a  $(q_k^{\text{init}}, \bar{v}_0)$ -rooted  $\{q^{\text{leaf}}\}$ -leaf-covering deduction tree of  $\mathcal{B}_k$ . Since at every  $q_k^{\text{loop}}$ -labelled node in  $\mathcal{D}$ , the value of  $d_k$  must be at least 1, it suffices to establish the following claim and apply it for the maximum  $h$ :

*Claim 18.1.* For each  $0 < h \leq \text{tower}(k-1)$ ,  $\mathcal{D}$  contains  $2^h$  incomparable nodes (i.e., none is a descendant of another) whose state label is  $q_k^{\text{loop}}$  and at which  $d_{k-1} + d'_{k-1}$  has value at most  $h$ .

In turn, by induction on  $h$ , that claim is a straightforward consequence of the next one. (For the base case of that induction, i.e.  $h = 1$ , apply the next claim with  $h' = 0$ .)

**Claim 18.2.** For each node  $n$  in  $\mathcal{D}$  whose state label is  $q_k^{\text{init}}$  and at which  $d_{k-1} + d'_{k-1}$  has some value  $h' < \text{tower}(k-1)$ , there must be two incomparable descendants  $n_1$  and  $n_2$  whose state labels are  $q_k^{\text{loop}}$  and at which the values of  $d_{k-1} + d'_{k-1}$  are at most  $h' + 1$ .

Consider a node  $n$  as in the latter claim. After the increment of  $d_{k-1}$  and the loops at  $q_k^1$  and  $q_k^2$ , the value of  $d_{k-1} + d'_{k-1}$  will be at most  $2(h' + 1)$ . If the first split divides  $d_{k-1} + d'_{k-1}$  equally, we are done.

Otherwise, we have a  $q_k^{\text{loop}}$ -labelled descendant  $n'$  of  $n$  at which  $d_{k-1} + d'_{k-1}$  has value at most  $h'$ . In particular,  $d_{k-1}$  is less than  $\text{tower}(k-1)$  at  $n'$ , so recalling the induction hypothesis regarding  $\mathcal{B}_{k-1}$ , the child  $n''$  of  $n'$  cannot be  $q_{k-1}^{\text{init}}$ -labelled. Thus,  $n''$  must be  $q_k^{\text{init}}$ -labelled, and the value of  $d_{k-1} + d'_{k-1}$  at  $n''$  is the same as at  $n'$ , so at most  $h'$ . We can therefore repeat the argument with  $n''$  instead of  $n$ , but since  $\mathcal{D}$  is finite, two incomparable descendants as required eventually exist.  $\square$

Relying on the properties of the BVASS  $\mathcal{B}_k$ , we now establish the hardness of lossy reachability, matching the membership in TOWER in Theorem 16 already for BVASS. Although we do not match the upper bounds when the system dimension is fixed, we remark that our simulation uses a number of counters which is linear in the height of the tower of exponentials with coefficient 2.

**Theorem 19.** *Reachability for lossy BVASS is TOWER-hard.*

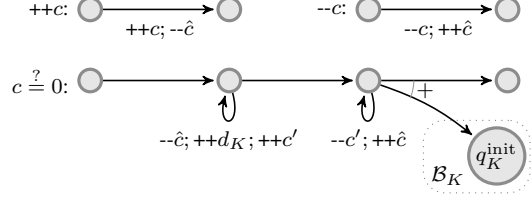
*Proof.* For a notion of Minsky machines that is similar to how ABVASS<sub>0</sub> were defined in Section 3.1, let such a machine be given by a finite set of states  $Q$ , a finite set of counters  $C$ , and finite sets of increment rules “ $q \xrightarrow{++c} q_1$ ,” decrement rules “ $q \xrightarrow{--c} q_1$ ” and zero-test rules “ $q \xrightarrow{c \stackrel{?}{=} 0} q_1$ .” By simulating a tape using two stacks, and simulating a stack using two counters, it is straightforward to verify that the following problem is TOWER-hard:

Given a Minsky machine  $\mathcal{M}$  and two states  $q_0, q_H$ , does  $\mathcal{M}$  have a computation that starts in  $q_0$  with all counters having value 0, ends in  $q_H$ , and is such that all counter values are at most  $\text{tower}(|\mathcal{M}|)$ ?

We establish the theorem by working with the equivalent top-down coverability problem (see Section 3.2.2). We show that, given a Minsky machine  $\mathcal{M}$  of size  $K$  and two states  $q_0, q_H$ , then a BVASS  $\mathcal{A}(\mathcal{M})$ , a state  $q_r$  and a finite set  $Q_\ell \stackrel{\text{def}}{=} \{q_H, q^{\text{leaf}}\}$  are computable in logarithmic space, such that  $\mathcal{M}$  has a 0-initialised  $\text{tower}(K)$ -bounded computation from  $q_0$  to  $q_H$  if and only if  $\mathcal{A}(\mathcal{M})$  has a  $(q_r, \bar{0})$ -rooted  $Q_\ell$ -leaf-covering deduction tree.

For each counter  $c$  of  $\mathcal{M}$ , there are three counters in  $\mathcal{A}(\mathcal{M})$  denoted  $c, \hat{c}, c'$ . The initial part of  $\mathcal{A}(\mathcal{M})$  employs a “weak Petri net computer” [16] for the tower function, namely a constant VASS with a designated start state, input counter, finish state and output counter, which given a natural number  $m$ , can compute  $\text{tower}(m)$  but non-deterministically may also compute a smaller value. (It is standard to construct such a VASS from weak routines for  $2m$  and  $2^m$ .) By means of the latter VASS, each counter  $\hat{c}$  in  $\mathcal{A}(\mathcal{M})$  is initialised to have value  $\text{tower}(K)$  (or possibly smaller). Recalling that the auxiliary VASS is constant, a simple pattern for incorporating it into  $\mathcal{A}(\mathcal{M})$  is to use fresh states and counters for each  $\hat{c}$ .

The main part of  $\mathcal{A}(\mathcal{M})$  consists of simulating  $\mathcal{M}$  from  $q_0$ , using the translations of increments, decrements and zero tests in Figure 5. For the increments and decrements,  $\mathcal{A}(\mathcal{M})$  also performs the opposite operation on the hatted counter, thereby keeping the sums  $c + \hat{c}$  constant. For the zero tests,  $\mathcal{A}(\mathcal{M})$  attempts by two loops



**Figure 5.** Simulating the Minsky operations.

and using the primed counter, to copy the hatted counter to  $d_K$  and then employ  $\mathcal{B}_K$  (see Figure 4) to verify that the latter is maximal (i.e., has value  $\text{tower}(K)$ ). Thus,  $\mathcal{A}(\mathcal{M})$  also has counters  $d_i$  for  $0 < i \leq K$  and  $d'_i$  for  $0 < i < K$ , and more precisely a variant of  $\mathcal{B}_K$  is employed that has the same dimension as  $\mathcal{A}(\mathcal{M})$  (and does not use the extra counters).

For each 0-initialised  $\text{tower}(K)$ -bounded computation of  $\mathcal{M}$  from  $q_0$  to  $q_H$ , it is straightforward to check that  $\mathcal{A}(\mathcal{M})$  can simulate it as follows:

- each counter  $\hat{c}$  is initialised to  $\text{tower}(K)$ ;
- in every simulation of a zero test  $c \stackrel{?}{=} 0$ , the values of  $c, \hat{c}, c', d_K$  are resp. 0,  $\text{tower}(K)$ , 0, 0 before the two loops, and 0,  $\text{tower}(K)$ , 0,  $\text{tower}(K)$  before the split;
- at every start of  $\mathcal{B}_K$ , the value of  $d_K$  is  $\text{tower}(K)$  and all other counters have value 0.

By Lemma 18, we obtain a  $(q_r, \bar{0})$ -rooted  $Q_\ell$ -leaf-covering deduction tree of  $\mathcal{A}(\mathcal{M})$ .

The other direction is more involved: we show that, if  $\mathcal{A}(\mathcal{M})$  has a  $(q_r, \bar{0})$ -rooted  $Q_\ell$ -leaf-covering deduction tree  $\mathcal{D}$ , then  $\mathcal{M}$  has a 0-initialised  $\text{tower}(K)$ -bounded computation from  $q_0$  to  $q_H$ . By construction,  $\mathcal{D}$  consists of a path  $\pi$  from which there are branchings to deduction trees of  $\mathcal{B}_K$ . The main part of  $\pi$  consists of the simulations of increments, decrements and zero tests as in Figure 5. From it, we obtain a 0-initialised  $\text{tower}(K)$ -bounded computation of  $\mathcal{M}$  from  $q_0$  to  $q_H$ , after observing the following for every counter  $c$  of  $\mathcal{M}$ :

- After  $\hat{c}$  is initialised in  $\mathcal{D}$ , the value of  $c + \hat{c} + c'$  is always at most  $\text{tower}(K)$ .
- For each simulation of a zero test of  $c$ , we have by Lemma 18 that the value of  $d_K$  is  $\text{tower}(K)$  before the split and is 0 after the split on the path  $\pi$ , and consequently that the values of  $c, \hat{c}, c'$  are 0,  $\text{tower}(K)$ , 0 (respectively) before the two loops.
- The value of  $c$  may erroneously decrease due to the branchings, but since that makes the value of  $c + \hat{c} + c'$  smaller than  $\text{tower}(K)$ , such losses may occur only after the last simulation of a zero test of  $c$ , and so cannot result in an erroneous such simulation.
- Similarly, only the last transfer of  $c'$  to  $\hat{c}$  may be incomplete (i.e., it does not empty  $c'$ ).  $\square$

Since lossy reachability reduces to reachability and by Proposition 10 and Proposition 11, this entails:

**Corollary 20.** *Provability in MELL, MELLW, and LLW is TOWER-hard.*

## 7. Concluding Remarks

Although connections between propositional linear logic and families of counter machines have long been known, they have rarely been exploited for complexity-theoretic results. Using a model of

	MELL	LL
with W	TOWER-hard, $\Sigma_1^0$ -easy	$\Sigma_1^0$ -c. [14]
with C	TOWER-c. 2EXP-c. [22]	TOWER-c. ACK-c.

**Table 1.** The complexity of provability in fragments and variants of LL.

	AVASS	BVASS	ABVASS $_{\bar{0}}$
Reachability	$\Sigma_1^0$ -c. [14]	TOWER-hard, $\Sigma_1^0$ -easy	$\Sigma_1^0$ -c.
Lossy reach.	2EXP-c. [4]	TOWER-c.	TOWER-c.
Incr. reach.	ACK-c. [23]	2EXP-c. [6]	ACK-c.

**Table 2.** The complexity of reachability problems in ABVASS $_{\bar{0}}$ .

alternating branching VASS, we have unified several of these connections, and derived complexity bounds for provability in substructural logics from the (old and new) bounds on ABVASS $_{\bar{0}}$  reachability, summarized in Table 1 and Table 2 respectively.

Our main results in this regard are the TOWER-completeness of provability in LLW and the new TOWER lower bound for MELL: the latter has consequences on numerous problems mentioned in Section 3, and entails for instance that the satisfiability problem for FO<sup>2</sup> on data trees is non-elementary [2, 7]. The ACKERMANN-completeness of MALLC and LLC is perhaps less surprising in the light of Urquhart’s results, but we take it as a testimony of the versatility of the ABVASS $_{\bar{0}}$  model.

The main open question remains whether BVASS reachability, or equivalently MELL provability, is decidable.

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