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Operational Semantics with Hierarchical Abstract Syntax Graphs*

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This is a motivating tutorial introduction to a semantic analysis of programming languages using a graphical language as the representation of terms, and graph rewriting as a representation of reduction rules. We show how the graphical language automatically incorporates desirable features, such as α -equivalence and how it can describe pure computation, imperative store, and control features in a uniform framework. The graph semantics combines some of the best features of structural operational semantics and abstract machines, while offering powerful new methods for reasoning about contextual equivalence.

All technical details are available in an extended technical report by Muroya and the author [11] and in Muroya's doctoral dissertation [21].

1 Hierarchical abstract syntax graphs

Before proceeding with the business of analysing and transforming the source code of a program, a compiler first parses the input text into a sequence of atoms, the *lexemes*, and then assembles them into a tree, the *Abstract Syntax Tree* (AST), which corresponds to its grammatical structure. The reason for preferring the AST to raw text or a sequence of lexemes is quite obvious. The structure of the AST incorporates most of the information needed for the following stage of compilation, in particular identifying operations as nodes in the tree and operands as their branches. This makes the AST algorithmically well suited for its purpose. Conversely, the AST excludes irrelevant lexemes, such as separators (white-space, commas, semicolons) and aggregators (brackets, braces), by making them implicit in the tree-like structure. It is always possible to recover the textual input, or rather an equivalent version of it, from the AST via a process known as *pretty-printing*.

A fair question to ask is whether the AST can be improved upon as a representation of program text, which captures grammatical structure while discarding needless detail. In pretty-printing we know how irrelevant lexemes can be manipulated to achieve a certain aesthetic effect. Redundant brackets can be elided to reduce clutter, white-space can be added or removed to improved alignment, and so on. Such details are accepted as irrelevant.

There is another, deeper level of detail in the text, which is irrelevant but not always appreciated as such: variable names. Whereas we know, formally, that bound variables can be systematically renamed (α -equivalence) the conventional AST will still remember their names, even though variable names induce bureaucratic complications having to do with scope and shadowing. Finally, there is yet another even deeper level of irrelevant detail in the program text, the order in which variables are defined, absent define-use dependencies between the definitions.

Consider the program text in Fig. 1, in which `def` is a binder associating a variable with a definition as text, akin to a macro, but respecting variable scoping rules. Variable `x` in line 3 could be renamed, on

*Extended abstract of invited talk

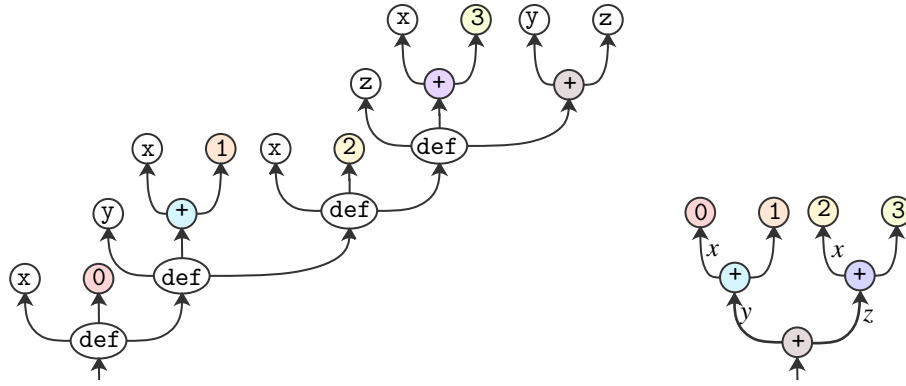


Figure 2: AST vs ASG for variable definition

lines 3-5, to something else to avoid shadowing the variable with the same name on line 1. Lines 1-2 and lines 3-4 can be swapped without changing the result. But these facts are not immediate from examining its AST in Fig 2 (left).

```

1  def x = 0
2  def y = x + 1
3  def x = 2
4  def z = x + 3
5  y + z

```

Figure 1: Bindings

Unlike ASTs, an abstract syntax graphs (ASG) do not treat binders and variables as nodes. Variables are instead represented as links, and binders assign target nodes corresponding to their definitions to the variable links. The ASG of the code in Fig. 1 is represented next to its AST in Fig. 2. To better understand the relation between the AST and the ASG, corresponding nodes are coloured and the links are labelled with variable names. The colour and the labels are not part of the definition of the graph structure, but are just used to aid understanding. The nodes corresponding to variable uses and definitions, left blank, are not part of the ASG. It is thus immediately obvious that the ASG is, by construction, quotiented both by α -equivalence and by the order of non-interfering variable bindings. This more general structural equivalence of lambda calculus terms has been dubbed “graph equivalence” by Accattoli et. al. [4].

```

1  def x = 2
2  def z = x + 3
3  z + z

```

Figure 3: Contraction

ASGs are also helpful when variables are reused, as in the Fig. 3 example. The AST and the ASG are showed side-by-side in Fig. 2, noting that the links corresponding to the variable z , used twice, now both point to its definition. This is why ASG are no longer trees, but directed acyclic graphs (DAGs). Formally, the ASGs are *hypergraphs* with the links a graphical representation of vertices and the nodes a graphical representation of hyperedges.

To represent *local* variable binding, as encountered in functions as opposed to simple variable *definition* discussed above, we note that local variable binding is always associated with *thunks*, i.e. code with delayed execution. This is related to the fact that conventional programming languages use normal-order reduction. In this evaluation strategy functions are considered values, i.e. there is no evaluation ‘under the lambda’. In other words, functions are thunks and locally-bound variables will always induce a thunk. Because thunks can be considered, operationally, as a single entity, it is convenient to represent them in their ASG form as a single node, labeled by the definition of the thunk, which is also an ASG. In other words, to model local variable binding in functions it is convenient to use graphs labelled by graphs, which are, formally, *hierarchical hypergraphs*.

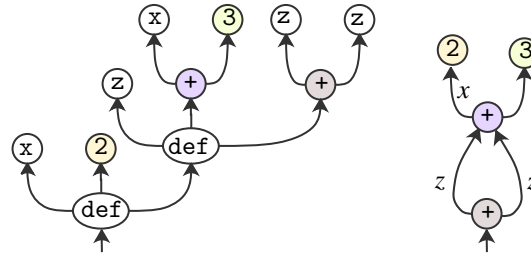


Figure 4: AST vs ASG for contraction

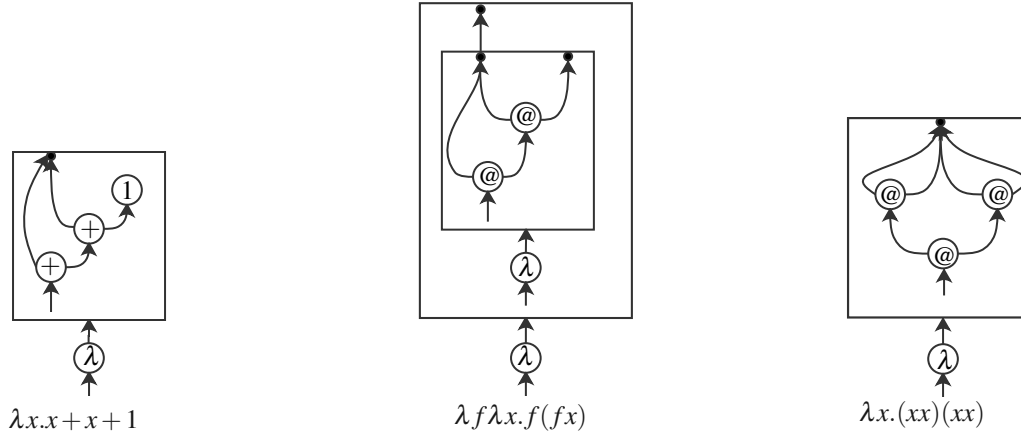


Figure 5: Hierarchical ASGs

To model variable behaviour in thunks correctly, our ASGs need to be *interfaced*, i.e. there needs to be a defined order on incoming links. If a thunk has m bound variables and n free variables then the first m incoming links of the ASG used as its label represent the bound variables, in the order in which they are bound. The last n incoming links represent the free variables, in some specified order. The node corresponding to the thunk will also have n incoming links, representing the definitions of its n free variables, in an order consistent with the order used by the label ASG. To make the correspondence more perspicuous we connect the links corresponding to the free variables from the labelling ASG to those of the node, as it causes no ambiguity. Fig. 5 shows several examples for hierarchical ASGs and the corresponding terms, with function application labelled as $@$. Note that thunks associated with lambda expressions are still explicitly linked to a lambda-labelled node. This is because in a programming language thunks can be used for expressions other than function definitions, as we shall see.

2 Operational semantics

The most widely used method for specifying programming languages is via *operational semantics* (OS). There are several versions of OS. We will focus on so-called *structural operational semantics* (SOS) in the style of Plotkin [27], in which a *transition relation* is defined on *configurations* consisting of a term t and some additional information (e.g. a program *store*, s, t), so that the definition of the relation is inductive on the structure of the term.

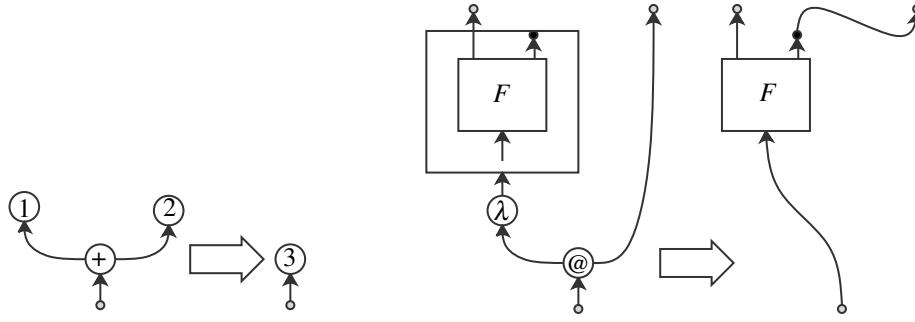


Figure 7: ASG rewrite as basic reductions

Typically the transition relation is written as $s, t \rightarrow s', t'$. There are two kinds of rules, *basic reductions* which perform operations (e.g. first rule in Fig. 6) and *simplification steps* which seek redexes structurally in the program text according to the evaluation strategy (second rule in Fig. 6). The latter are usually written in natural-deduction style. For example, the rule specifying that $+$ is evaluated left-to-right is the second rule in Fig. 6. Note how the first operand e_1 is evaluated to e'_1 and, in the process, the store s may change to s' .

$$\frac{s, 1 + 2 \rightarrow s, 3}{\frac{s, e_1 \rightarrow s', e'_1}{s, e_1 + e_2 \rightarrow s', e'_1 + e_2}}.$$

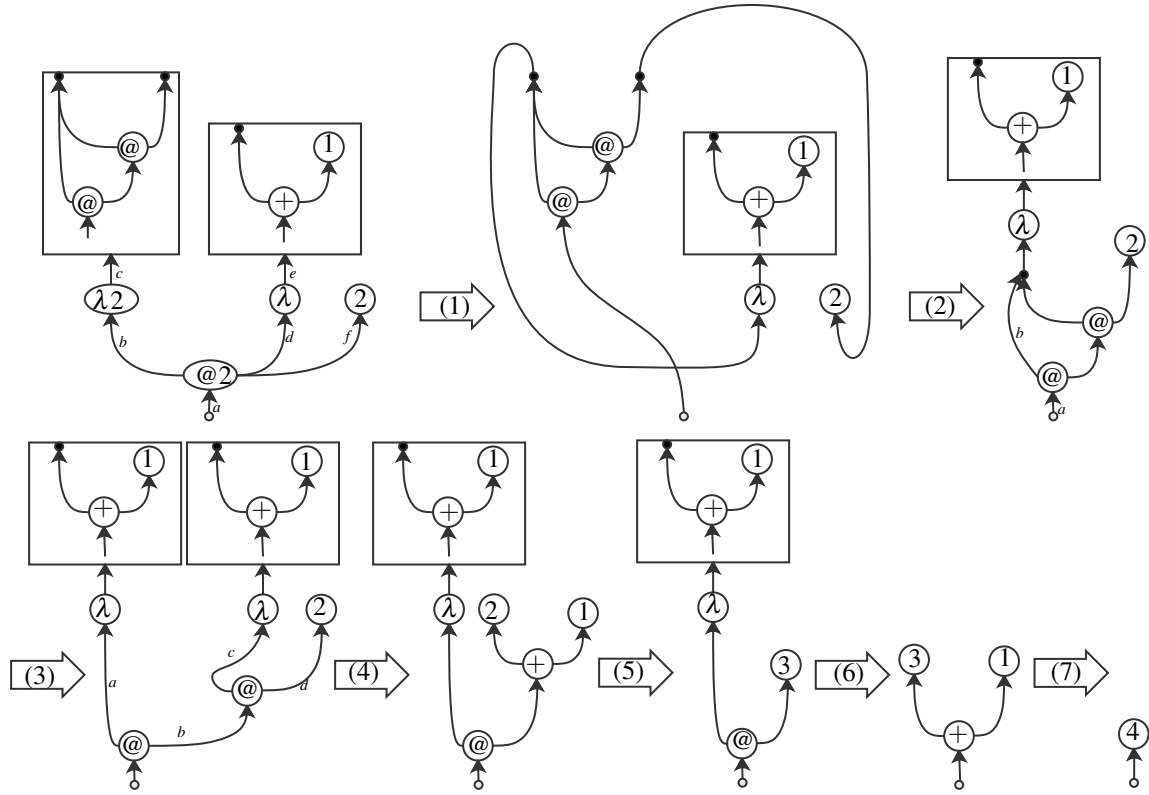
Figure 6: SOS (example rules)

SOS can be naturally formulated on ASGs rather than on terms. Basic reductions correspond to graph rewrites and simplification steps to a graph traversal algorithm which seeks the redexes. The basic reduction in Fig. 6 is shown as a graph rewrite in Fig. 7, along with the rule for β -reduction. The former is quite obvious, but the latter is more interesting. It consists of the deletion of the abstraction-application pair, the ‘unboxing’ of the thunk by extracting the label of the thunk node and using it in the top-level graph, the re-wiring of the bound variable, now open, to the argument, and using the root node of F as the overall root node. For the β rule the graphs involved in the rewrite must also be interfaced, with the interface nodes highlighted in grey. Also note that the rule is actually the *small* β rule used in calculi of explicit substitution which reduces $(\lambda x.F)M$ to $\text{def } x = M \text{ in } F$ [1].

One aspect of the ASG-based evaluation which needs to be clearly explicated is sharing. The DAG structure of the ASG can be refined by introducing special sharing nodes, which, unlike operation nodes, would be allowed to have multiple incoming links. Sharing nodes have a special behaviour during evaluation, managing the process of systematic copying of sub-graphs.

To evaluate an ASG in a way that is consistent with left-to-right call-by-value the traversal is depth-first and left-to-right, without reaching inside thunks, starting from the unique root. The current link in the traversal is called the *focus*, and it can move *up* (i.e. away from the root) or *down* (i.e. towards the root). When the focus is moving up and it encounters a copy node it will copy the node shared by the copy node, inserting further copy nodes on its outgoing links. As the focus is moving down, whenever it passes a node which has an associated rewrite rule it will exercise it, then change direction and move up again (*refocussing*).

In Fig. 8 we show the key steps in the evaluation of the expression $(\lambda f x. f(fx))(\lambda x. x + 1, 2)$. We use the labels of $\lambda 2$ and $@ 2$ for definition and use of a function with two arguments. Step (1) is reached after the focus moves along the path *abcdefa*, at which point the rewrite is performed, unboxing the thunk and attaching the arguments to the nodes made available. Step (2) is simply rearranging the ASG in a more readable format. Step (3) is the copying of the node corresponding to the function $\lambda x. x + 1$

Figure 8: Evaluation of $(\lambda fx.f(fx))(\lambda x.x+1,2)$.

after the focus traverses path ab . Step (4) is the β rewrite applied after the focus traverses path $abcd$. Step (5) is an arithmetic reduction, followed by another β rewrite and a final arithmetic reduction.

The examples in this section (abstraction, application, arithmetic) deal with what is usually deemed *pure* functional programming, case in which the configuration used by the SOS is the term itself. Expanding the SOS of a language to incorporate effects usually requires revising the format of the configuration of the SOS, which in turn requires reformulating the rules for the preexisting operations. This is a major fragility of the SOS approach, since the revision of the format invalidates any technical results and require laborious re-proving [12]. ASGs can be enhanced with a single new node which will allow the formulation of most known effects, namely an *atom* node, in the sense of [26]. The ASG OS for a pure language then only differs from the ASG OS of an impure language in that the atom nodes are not involved. The atom node, just like a sharing node, allows multiple incoming links. However, during evaluation, the atom node does not trigger a copying of the node at the end of its outgoing link, but is instead treated as an endpoint by the ASG traversal strategy. Indeed, just as computations are not performed inside of thinks they are also not performed inside of the store. This insight, that the essence of effectful computation is the presence of atoms in the OS is originally due to Pitts, but it turns out to be most effective in ASG-based OS [24].

Fig 9 shows the basic rule for assignment, with the atom indicated as an unlabeled white node. The atom is made to point to the second operand of the assignment operator, while the assignment operator itself reduces to the dummy value inhabiting the unit type. In the process, whatever the atom was attached to before may become inaccessible from the root of the ASG, therefore *garbage*. Also note that the effect

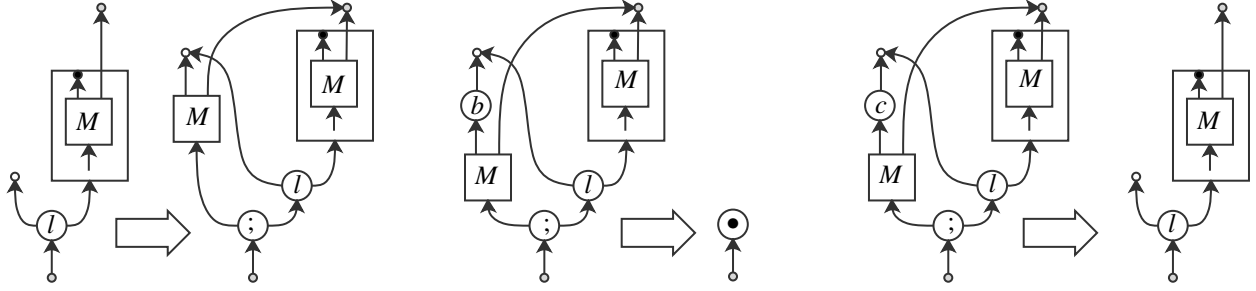


Figure 10: Control in ASG OS

of the assignment is manifest only because other parts of the ASG may point to the atom, a link which is persistent due to the value-like behaviour of the atom.

The SOS of a programming language can be further refined (*distilled*) into an abstract machine, which gives a more explicit representation of the simplification rules via manipulation of context [31]. From this point of view, the ASG representation of the SOS is already an abstract machine, in the sense that it can give a cost-accurate model of execution of the language.

Another appealing feature of abstract machines is that they can model control-transfer operations more conveniently than SOS. It is not impossible to use SOS for this, but the format of the transition system needs to be significantly revised, making the transitions themselves labelled [29].

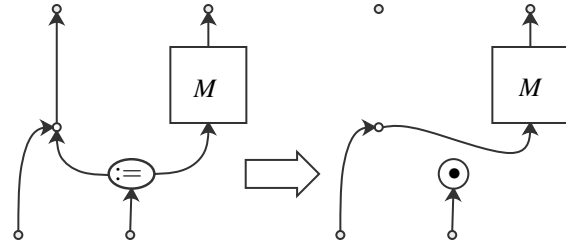


Figure 9: Assignment in ASG OS

Since the ASG OS is formulated via arbitrary rewrites, control can be dealt with in a straightforward way. Fig 10 shows a labelled version of C-style *break/continue* statements. The operations involved are loop body definition (l), sequential composition ($;$), break (b), and continue (c). The atom used as the first operand of l becomes bound to the label which is the bound argument of M , used to anchor a point in the ASG so that the control operations of break or continue can determine where to jump to. If M terminates normally then the whole cycle repeats. Unlike conventional C break and continue these variants are labelled, and the labels are first-class citizens, i.e. they can be passed as arguments to or returned from functions.

An interactive evaluator for a variety of programming language features can be found online.¹

3 Reasoning

SOS was originally considered too ‘low level’ to reason about equivalence in programming languages, at least in contrast with denotational semantics. However, SOS was considered more ‘high level’ than alternative operational specifications of programming languages such as abstract machines. In time, a large variety of powerful techniques for reasoning with SOS-like specifications proved that this is indeed a useful formalism for reasoning about equivalence [25] whereas abstract machines remained useful due

¹<https://tnttodda.github.io/Spartan-Visualiser/>

to their ability to model the cost of evaluation and as a gateway to compiler development [19]. The ASG OS seems to combine felicitously some of the best features of SOS and abstract machines including, as we shall see, the ability to reason about observational equivalence.

In fact, the graph formulation of the OS makes it possible not just to reason about equivalence, but to formulate a powerful characterisation theorem which establishes equivalence by using some simpler combinatorial criteria. We must first ‘tame’ the OS by restricting ourselves to sets of rules which are *deterministic* and *refocussing*. The first concept is the standard one. The second, initially formulated by Danvy et. al., means that following a basic reduction the focus could be kept either at the point where the rewrite occurs, or moved to the root of the graph, with equal effect [9]. Indeed, all the rules we have presented in this tutorial are refocussing.

Equivalences are also formulated graphically, as families of relations on *templates*, i.e. sets of graphs with the same interface. For a fixed abstract machine a template is said to be *input-safe* if evaluation from any input link preserves the relation. Note that, unlike a SOS, we can talk about the evaluation of an ASG which is not a program, in fact not even a term, since evaluation is just a byword for traversal and reduction. A template is said to be *output-closed* if in the course of evaluation no output link will ever be reached. Finally, a template is said to be *robust* if it is preserved by all rewrite rules of the language. The main theorem can be simply stated as:

Theorem. (Characterisation [11, Sec. 6]). *Robust templates induce observational equivalence.*

The conditions used to establish equivalence via the Characterisation Theorem are all elementary and proved by case analysis. Moreover, the theorem allows for *robust* proofs of equivalence in the sense that they can withstand language extensions. For example we can prove the β law for a pure language can be extended to a language with imperative store just by showing that the templates used in formulating the law are robust relative to the new rules for variable creation, dereferencing, and assignment (Fig. 4). Which happens to be the case. By contrast, conventional proofs of equivalence are fragile, and are invalidated by even mild language extensions.

4 Related work

This is an elementary tutorial introduction and extended motivation for the *hypernet semantics* of programming languages [11], which is a streamlined and generalised version of the *Dynamic Geometry of Interaction (GoI) Machine* [22]. They are the outcome of an effort initially motivated by the understanding of call-by-value and effectful computation from a GoI perspective [16, 23].

Graph-based intermediate representations (IR) are established in compiler construction [7] and in the formulation of abstract machines for functional languages [17]. However, the origin of the approach describe here lies elsewhere, in *proof nets*, a graphical representation of proofs in Linear Logic [13] and especially in their generalisation as *interaction nets* [18]. Interaction nets already exhibit the hierarchical structure we employ here, which is used to model binding and higher-order structures. Hierarchical graphs are also used elsewhere in semantics, for example as diagram languages of processes known as *bigraphs* [20].

The connection between linear logic and its varieties and certain monoidal categories kindled significant progress in diagrammatic languages [30]. For instance, traced monoidal categories, used as models of lambda calculus with cyclic sharing [15], led to the development of a hierarchical graph syntax for closures [28] remarkably similar to the one described here. In terms of the treatment of graphs as combinatorial objects, much of the literature considered them rather informally and a formalisation of proof

nets as hypergraphs was given much later [14].

More recently, work by Accattoli has examined the interesting interplay between term-based and graph-based formulations of the call-by-value lambda calculus [2], even though his motivations are somewhat different than ours, as illustrated by this quotation:

It is far from easy to realize an isomorphism between terms and nets, as it is necessary to take care of many delicate details about weakenings, contractions, representation of variables, administrative reduction steps, and so on. [...] More generally, such a strong relationship turns the calculus into an algebraic language for proof nets, providing a handy tool to reason by structural induction over proof nets.

In fact, a properly formalised graphical syntax can be just as powerful and just as rigorous as an algebraic language. Moreover, the graphical language can be both simpler and better specified than the term language, for example in the case of the calculus of explicit substitutions, which lacks a proper formulation of α -equivalence [3].

To conclude, we see the ASG operational semantics as a first step in an exciting and potentially fruitful direction. Graphical languages are starting to emerge as a new and genuine formalism which can give alternative, and sometimes improved, representations to theories in fields as different as quantum computation [8], linear and affine algebra [5], digital circuits [10], signal flow [6] and more. The motivations for this emergence are mixed, from the raw intuitive appeal of visual representations to improved algorithmic properties. Examining how this methodology can be extended to programming languages is an intriguing next step which brings together a number of existing ideas and concepts and can unify existing gaps between semantics of programming languages and compiler-related techniques.

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