

# Using Objects of Measurement to Detect Spreadsheet Errors

**DRAFT**

Michael J. Coblenz, Andrew J. Ko, and Brad A. Myers  
School of Computer Science  
Carnegie Mellon University  
Pittsburgh, PA 15213 USA  
*mcoblenz@andrew.cmu.edu, ajko@cmu.edu, bam@cs.cmu.edu*

## **Abstract**

*There are many common errors in spreadsheets that traditional spreadsheet systems do not help users find. This paper presents a statically-typed spreadsheet language that adds additional information about the objects that spreadsheet values represent. By annotating values with both units and labels, users denote both the system of measurement in which the values are expressed as well as the properties of the objects to which the values refer. This information is used during computation to detect some invalid computations and allow users to identify properties of resulting values.*

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## 1. Introduction

Spreadsheets are used both by home users for small calculations as well as by business users for mission-critical applications involving millions of dollars. Unfortunately, errors in spreadsheets are as ubiquitous as spreadsheets themselves, with 20% to 40% of spreadsheets containing errors [1].

Recent work has focused on software engineering techniques that may be applied to the spreadsheet development process. For example, Rajalingham et al. described improvements in the process itself [8], and Rothermel et al. described tools to help test and debug spreadsheets [9]. These are useful additions to an already successful language paradigm, but they do not attempt to improve the language itself. Work on improving spreadsheet languages has focused primarily on augmenting them with units. XeLda [2] allows users to define their own, and propagates units through computations. Apples and Oranges [4] defines a somewhat different form of unit, based on inferences from headers in tables of spreadsheets.

While these approaches can help users detect errors in values and units, errors based on the object being measured can go unnoticed. In this paper, we introduce a new spreadsheet system called SLATE (“A Spreadsheet Language for Accentuating Type Errors”), which separates the unit from the object of measurement, and defines new semantics for spreadsheets so that both the unit and the object of measurement are taken into consideration. Unlike the standard semantics for units, the semantics of operations on objects of measurement are not obvious; it is necessary to choose an intuitive approach for propagating information through calculations. By redefining the semantics of traditional spreadsheet operations, such as addition and multiplication, the system can generate additional information about results that reveals formula errors.

For example, a user might mistakenly multiply pounds of apples by the price per pound of oranges. A traditional spreadsheet showing only values would hide this error by displaying only the result, in dollars. Even considering units would not reveal this error. SLATE reveals the problem by showing that the result has properties of both apples and oranges:

$$10 \text{ lb. (apples)} * \$0.50 / \text{lb. (oranges)} = \$5 \text{ (apples, oranges)}.$$

In the next section, we briefly discuss related work. We then give an example of an error that SLATE would help the user detect, but other spreadsheets, such as that described in [4], would not. Next, we introduce core concepts of the language, and in the fifth section, give a detailed description of the

operators of the language and justifications for their design. We follow this with a discussion of user interface issues for this language, and conclude with future steps for SLATE.

## 2. Related Work

Like SLATE, other systems have had the goal of improving on the spreadsheet paradigm. Forms/3 [5] takes a functional programming perspective, and extends the full functional programming paradigm to a spreadsheet context. Forms/3 avoids the requirement of rows and columns, instead allowing any configuration of cells. We adopted this philosophy in SLATE: although our examples are in a standard table layout, the language itself would be suitable for another visual arrangement of cells.

Apples and Oranges [4] is the most closely related work. In it, Erwig and Burnett developed a unit system whereby the system inferred units for cells using a header cell inference algorithm [6]. The system defines the spreadsheet operations in terms of its unit system, and flags cells if its inference algorithm suggests an error. However, the inference algorithm is opaque, and if users do not format the spreadsheet as the authors intended, units may be inferred incorrectly (although Burnett and Erwig suggested in [7] ways in which users may customize the inference process). Furthermore, because the units can become very complicated, they are not suitable for display to users. Units are also limited to header data; no other data can be used.

Kennedy describes an ML-style functional programming language that includes dimensions [3]. Although it is not presented in a spreadsheet context, it is groundwork for statically-typed languages that include dimensions. Like other systems that include only units or dimensions, it cannot detect errors in objects of measurement.

## 3. An Example: Orchard Records

To illustrate how SLATE reveals errors, consider Figure 1, where a user attempted to calculate revenues for two types of fruit: apples and oranges. Instead of multiplying each weight of fruit by the corresponding cost, the user accidentally multiplied each weight by the cost per pound of apples. Conventional spreadsheets only display the result of the calculation, so the source of the error is not visible. Spreadsheets that consider only units would not reveal this error either, since both values under

consideration have the same units: \$ / lb. Because of the particular values in the cells, the user is unlikely to find this error by estimating the correct result and comparing to the computed values. In fact, the mistake has been completely hidden, only to be found by a careful inspection of the formulas.

SLATE reveals these errors by displaying additional information in the cells: in addition to displaying a unit, it displays a label, which is a list of attributes pertaining to the value in the cell. To visually separate them from the unit, labels are enclosed in parentheses when displayed.

In Figure 2, the same calculation from Figure 1 is performed in SLATE. In the “Revenue” column, the amounts are treated as measurements of fruit. The first row measures the cost of apples. The second row, however, appears to measure the cost of fruit that is simultaneously apples and oranges. This is obviously wrong; the user expected the cell to have only the attributes of oranges, since the calculation has nothing to do with apples. By computing and displaying these labels based on the labels the user entered for the original information, the system can help users detect otherwise hidden errors.

The work described in [4] would not find this error. Since both factors of the product in the incorrect cell have headers other than **1**, the resulting unit would be **1 & (Revenue & Fruit [Oranges])**, which is a legal unit according to the system described.

#### 4. Language Introduction

In this section, we discuss the additional data that SLATE must maintain to reason about units and labels.

##### 4.1. Values, Units, and Labels

In SLATE, every expression has three attributes: a value, a unit, and a label. The value is the same as spreadsheets would normally contain. Units, such as meters, kilograms, and seconds, indicate the way in which a measurement was made. They capture information about the scale at which the measurement was taken and the dimensions of the measurement

Apples (per lb.)	Oranges (per lb.)
\$0.45	\$0.50

Fruit	Fruit Sold (lbs.)	Revenue
Apples	312	\$140.40
Oranges	399	\$179.55

**Figure 1. An incorrect calculation in a spreadsheet.**

(although this system does not treat dimensions, such as weight, separately from the units, such as pounds, as discussed in Kennedy [3]). SLATE adds *labels*, which define characteristics of the objects of measurement. For example, a cell referring to 25 pounds of apples might read “25 lbs. (apples)”. In this example, the label is (apples). A cell referring to apples picked in September might have the label “(apples, September)” because the value in the cell has characteristics of both apples and September.

A	B	C
1	Fruit Prices	
2	\$0.45 / lb. (apples)	\$0.50 / lb. (oranges)
3		
4	Fruit Sold	Revenue
5	312 lb. (apples)	\$140.40 (apples)
6	399 lb. (oranges)	\$179.55 (apples, oranges)
7		
8		
9		
10		
11		
12		

**Figure 2. The spreadsheet from Figure 1, using SLATE. The revenue for oranges is incorrect. SLATE computed the contents of the Revenue cells, including the labels.**

#### 4.2. Contexts

Since SLATE must understand arbitrary objects being measured, it must be customizable to work for many different kinds of objects. For example, a construction company expects a spreadsheet to understand plywood and concrete; a farm expects it to understand fruit, vegetables, and fertilizer. An interior decorator would like “orange” to refer to a color, whereas an orchard manager would like “orange” to refer to a kind of fruit. These are different, since they have different subtypes: the color might have subtypes of “dark orange” and “red-orange,” but the fruit might have subtypes of “Navel” and “Valencia.”

To accomplish this, each spreadsheet refers to two contexts: a unit context and a label context. The unit context defines the base units that are available to the user. Base units are the primitive units that, when multiplied, form other units; thus, units in spreadsheets are formed from these base units. The “quantity” unit is a special case of a base unit, and is used for referring to quantities when counting discrete objects, such as “4 quantity (apples)”. It may be abbreviated “qty.”

The label context forms the core of this project. The structure of the label context reflects the observation that many real-world concepts and objects are hierarchical. Operations are defined on the labels so that generalizations up the hierarchy take place where appropriate. Therefore, the label context is a directed acyclic graph, where each node is a particular concept. There is an edge from node  $n_1$  to node  $n_2$  if objects of type  $n_2$  have all of the properties of objects of type  $n_1$ . For example, in Figure 3, there is an

edge from “Apples” to “Red Delicious” because red delicious are a kind of apple. Red Delicious apples have the properties of apples, and also some additional properties that not all apples share.

The example label context in Figure 3 might be suitable for a small orchard. The `Something` node represents the most general type of object; it is named as such to warn the user of a potentially dangerous generalization.

Although trees might suffice as a representation for label contexts, they would impose some artificial constraints. For example, in a label context for automobiles, SUVs might be considered to be both cars and trucks; this is represented more concisely in a directed acyclic graph, which SLATE supports.

## 5. Language Specification

### 5.1. Units

A unit context, denoted by  $\Gamma$ , is a set of base units. A base unit is used as in Kennedy’s work [3]; it can be thought of as a unit which cannot be expressed in simplest form as a product of other units.

A unit is a product of integer powers of base units. Let  $B$  range over elements of  $\Gamma$ . Then units  $\mu$  are defined as follows, with  $n \in \mathbb{Z}$  (i.e.  $n$  is an integer):

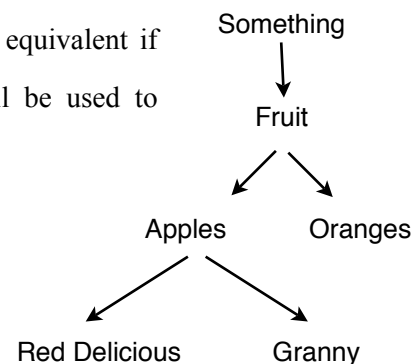
$$\mu ::= 1 \mid \mu \cdot B^n$$

1 is the identity unit; it is never displayed to users.

Each unit has a canonical representation. In particular, the base units are sorted lexicographically (there may be at most one base unit with a given name). There may be no more than one appearance of a particular base unit in the canonical representation; multiple appearances are combined by summing the exponents. Units are considered to be equivalent if they have identical canonical representations. The symbol  $=$  will be used to represent equivalences.

### 5.2. Labels

A label context  $\Lambda$  is a directed acyclic graph, comprised of concepts ( $C$ ) and edges ( $E$ ), where there is a path from a



Something node to each other node. Thus,  $\Lambda = (C, E)$ . Each node in the graph represents a concept.  $c \in \Lambda$  will serve as an abbreviation for  $c \in C$ .

A label  $\lambda$  is a disconnected set of nodes from the set  $C$ . It represents objects that have the properties of all of its nodes. For example, the set  $\{\text{apple}, \text{ripe}\}$  is a label that represents the set of objects that are apples and are also ripe. Of course, this label is only defined in an appropriate context;  $(\text{apple}, \text{ripe})$  is not a valid label otherwise. The empty label,  $\{\}$ , represents the `Something` node. The relation *descendent*  $(\lambda_1, \lambda_2)$  holds if and only if there is a path in  $\Lambda$  from  $\lambda_2$  to  $\lambda_1$ .

The relation  $\leq_\ell$  between pairs of labels is defined as follows:

$$\lambda_1 \leq_\ell \lambda_2 \Leftrightarrow \forall c_2 \in \lambda_2 . \exists c_1 \in \lambda_1 . \textit{descendent} (c_1, c_2)$$

*Claim:*  $\leq_\ell$  is a partial ordering on labels.

*Proof:* Reflexivity: *descendent*  $(\lambda, \lambda)$ , since  $\forall c \in \lambda$ , there is a trivial path from  $c$  to  $c$ .

Antisymmetry: Suppose  $\lambda_1 \leq_\ell \lambda_2$  and  $\lambda_2 \leq_\ell \lambda_1$ . The fact that  $\lambda_1 = \lambda_2$  follows directly from antisymmetry of the descendent relation on directed acyclic graphs: let  $c_1 \in \lambda_1$  and  $c_2 \in \lambda_2$ . We have *descendent*  $(c_1, c_2)$  and *descendent*  $(c_2, c_1)$ , so  $c_1 = c_2$ .

Transitivity: Suppose  $\lambda_1 \leq_\ell \lambda_2$  and  $\lambda_2 \leq_\ell \lambda_3$ . Let  $c_3 \in \lambda_3$  be given. By the definition of  $\leq_\ell$ ,  $\exists c_2 \in \lambda_2$  such that *descendent*  $(c_2, c_3)$ . Likewise,  $\exists c_1 \in \lambda_1$  such that *descendent*  $(c_1, c_2)$ . But elementary properties of graphs show that the descendent relation is transitive, so we have *descendent*  $(c_1, c_3)$ , as required.  $\square$

### 5.3. Types

Together, the unit and label form a type:  $\tau = (\mu, \lambda)$ . The labels impose a subtyping relation  $\leq$ , defined as follows:

$$(\mu_1, \lambda_1) \leq (\mu_2, \lambda_2) \Leftrightarrow \mu_1 = \mu_2 \text{ and } \lambda_1 \leq_\ell \lambda_2$$



## 5.4. Abstract Syntax for Expressions

Let  $f$  represent a floating-point value, and  $\epsilon$  the empty expression.  $ref$  represents a reference to another cell;  $range-ref$  represents a reference to a set of cells. An expression  $e$  is:

$$e ::= \epsilon \mid f \mid \mu \mid \lambda \mid e + e \mid e - e \mid e / e \mid e * e \mid ref \\ \mid MAX(range-ref) \mid MIN(range-ref) \\ \mid AVG(range-ref) \\ \mid string$$

A future version of this work will include boolean values and additional functions; they are not included here for simplicity.

## 5.5. Addition and Subtraction

Expressions (other than those that have errors in evaluation) may be added or subtracted if and only if they have equivalent units. Errors are propagated, so that if an operand has an error in evaluation, so does the result. Values are simply added or subtracted; no conversions are performed.

The restriction to permit adding or subtracting only expressions with equivalent units maintains the standard interpretation of units. Because units express the measurement system, permitting these operations for values of different units would result in nonsense. For now, there is no support for automatic unit conversion.

To determine the label of the result of an addition or subtraction operation, SLATE derives the least general label that includes all of the properties in both of the operands.

Let *intersection-with-paths* be a function from label pairs to labels, which when given a pair of labels  $(\lambda_1, \lambda_2)$  returns the set of nodes:

$$\{n \mid (n \in \lambda_1 \text{ and } \exists n' \in \lambda_2: \text{descendent}(n', n)) \text{ or} \\ (n \in \lambda_2 \text{ and } \exists n' \in \lambda_1: \text{descendent}(n', n))\}$$

Let *parents* be a function from labels to labels, which when given a label  $\lambda$ , returns the union of the sets of parents of the nodes in  $\lambda$  for the given context.

The label derived for addition and subtraction is as follows:

```
fun add-sub-labels ( $\lambda_1$ ,  $\lambda_2$ ) =
  if  $\lambda_1 = \{\}$  then  $\{\}$ 
  else if  $\lambda_2 = \{\}$  then  $\{\}$ 
  else
    let intersection =
      intersection-with-paths ( $\lambda_1$ ,  $\lambda_2$ )
    in
      intersection  $\cup$ 
        add-sub-labels (parents
          ( $\lambda_1 \setminus$ intersection),
          parents ( $\lambda_2 \setminus$ intersection))
    end
```

This function defines a unique label, given  $\lambda_1$ ,  $\lambda_2$ , and the context  $\Lambda$ , since it is deterministic, and terminates (the DAG is finite).

For example, using the context in Figure 3:

$$5 \text{ lbs. (apples) } + 2 \text{ lbs. (oranges) } = 7 \text{ lbs. (fruit)}$$

because apples and oranges are both fruit. Similarly, in a context where September has been defined:

$$5 \text{ lbs. (apples, September) } + 2 \text{ lbs. (oranges, September) } = 7 \text{ lbs (fruit, September).}$$

Notice how apples and oranges are combined into fruit, but because September is in both labels, it is copied into the final label. Likewise:

$$5 \text{ lbs. (apples) } + 2 \text{ lbs. (oranges, September) } = 7 \text{ lbs. (fruit)}$$

in a context where the parent of September is *Something*.

The goal of this choice of definition of addition and subtraction is for the labels to succinctly express the properties of the resulting object. Addition can be thought of as a union of sets of objects. The label of the result expresses the properties that are guaranteed of an arbitrary element of the result. The only properties that can be guaranteed are those that are shared among all the objects in the set.

It might seem, on the surface, that subtraction could be defined in a manner opposite to addition, since the two operations are inverses: when evaluating  $e_1 - e_2$ , subtraction would keep the label of  $e_1$ , but would be illegal if  $e_2$  were not a subtype of  $e_1$ . This is attractive because it would seem to preserve the semantics of labels referring to sets. However, this approach would be inconsistent because it would cause the label of the result of an addition operation to depend on the signs of the values. This instability would

be especially confusing for a user, who could find that small changes in values in one part of a spreadsheet caused errors in a dependent part of the spreadsheet due to sign changes in dependent values.

Another possible choice of definition for addition and subtraction would be to require equality in the labels, in addition to equivalence in the units. This would be overly restrictive, however, since users frequently need to compute sums of different kinds of objects. For example, for the purpose of finding the total weight of a shipment consisting of many different items, the fact that the items are different is irrelevant; the user only wants the total weight. SLATE expresses this by choosing the most general label (perhaps `Something`). The user is therefore alerted to the fact that the items are different. If this is an error, the fact that the label unexpectedly became more general would serve as a warning to the user.

## 5.6. Multiplication and Division

Multiplication and division of two non-error values is always legal; the resulting unit is the product of the units of the operands. Errors are defined to propagate, so that if an operand has an error in evaluation, so does the result. For labels, multiplication and division are defined so that the result label includes all of the properties of the operands' labels. Note that because labels are attached to the value rather than the unit, they are never in the denominator of any expression.

It would be redundant for a label to contain both a node and one of its ancestors; in these cases, the ancestor is discarded. Assume that the function *eliminate-ancestors*, when given a label  $\lambda$ , returns a new label  $\lambda'$  that is the same as  $\lambda$ , but the ancestors of ancestor-descendent pairs in  $\lambda$  have been removed. Multiplication and division of labels is implemented as follows:

```
fun mult-div-labels ( $\lambda_1$ ,  $\lambda_2$ ) =  
  eliminate-ancestors ( $\lambda_1$  U  $\lambda_2$ )
```

For example:

```
2 qty. (apples) * $0.50 / qty. (apples) = $1.00 (apples)
```

But:

```
2 qty. (apples) * $0.50 / qty. (oranges) = $1.00 (apples, oranges)
```

The label (apples, oranges) is different both syntactically and semantically from the label (fruit). The label (apples, oranges) denotes objects that have all the properties of apples and also all the properties of oranges; the user will observe that not only was one of apples or oranges not expected in the result, but that there are no objects like this. The label (fruit) would denote objects that have the properties of fruit, without specifying what other properties of apples or oranges they might have.

The choice of definitions for multiplication and division represents a tradeoff between recording the history of the computation—resulting in large, unreadable labels—or erasing it, and hiding potential errors. One concern with the definition chosen here is that it may maintain too much of the computation history. For example, the product of a list of different items would result in a very large label, since SLATE would take the union of the elements of the operands' labels. However, spreadsheets are not commonly used to compute products of large sets of items; although this is a potential use (for example, in calculating geometric means), we chose to optimize for the common case: users sum large lists, but tend to multiply only small lists. Furthermore, in most spreadsheets, the chain of computation may be relatively short. If this is the case, the label will probably not become too large.

An alternative to the union definition we chose, arising from the concern above, is to use intersections of the sets, rather than unions. The intersection operator would be defined similarly to the algorithm used for labels in addition and subtraction. However, although this approach would result in smaller labels, multiplication does not correspond to the item-property semantics described for addition and subtraction, so its interpretation would be unclear: multiplication in this context is not simply repeated addition, as shown by the behavior of units with multiplication. Furthermore, this alternative definition would hide errors: rather than indicating errors by displaying unexpected attributes, it would require users to notice the absence of expected attributes.

A natural question is whether this definition should also be used for addition and subtraction. However, the observation that addition is commonly used for lists of dissimilar items precludes this choice, since it would result in commonly having very long, unreadable labels. Further, it would break the semantics of labels as expected for addition: items in the result set would have only some of the properties of the label attached to the result, rather than all of them. This property is less important for multiplication and division, however; users familiar with operations with units know that units behave differently for multiplication and division than for addition and subtraction.

Another possible choice would be to define labels so that multiplication and division could be performed in a manner similar to those operations on units. In particular, there would be no simplification between labels with multiplication; the system would generate exponents if labels were identical, and cancel identical labels on multiplication if their exponents summed to zero. Division would be defined as the inverse of multiplication. This definition, despite its intuition and appeal, is not an appropriate choice for this system. Because of the large variety of possible labels, cancellation occurs much less frequently than it would occur with units. The result is that labels become very complicated, and therefore unreadable. For example, under this interpretation:

$$10 \text{ lbs. (red delicious) } * \$0.50 \text{ (apples) / lb.} = \$5 \text{ lbs. (red delicious) lb. (apples) / lb.}$$

No cancellation occurs in this example, resulting in a complicated, unreadable label. Users would likely choose to ignore the label rather than examining it.

One refinement attempt would be to consider labels to be contravariant in the denominator, meaning the system would cancel labels if the label in the denominator is a subtype of the label in the numerator. This would improve the previous example, resulting in \$5. However, even in cases where cancellation occurs, the system would lose important information as computation proceeded. The value \$5 does not reflect the fact that it is a measurement of red delicious apples (or even, more generally, apples). This loss of information can hide errors caused by improper uses of this computed value. For example, it might be incorrectly added to \$10 (oranges), under the mistaken assumption that the \$5 was a measurement of oranges. This would result in \$15, hiding the fact that this is in fact fruit. Users would begin to ignore the frequent disappearance of labels, causing them to also ignore potential errors.

## 5.7. Aggregate Operators

The aggregate operators defined in SLATE are MAX, MIN, and AVG. For all of these operators, the units of the operands must be equivalent (otherwise, comparisons or additions of the values would be meaningless).

The label of the result is as defined for addition and subtraction, extended to  $n$  labels instead of only two. For MAX and MIN, it would be tempting to instead copy the label from the maximum or minimum value into the result's label. However, the label of the result should depend only on the labels of the operands, rather than on their values. For example, suppose a user calculated the MAX of 3 qt y.

(apples) and 5 qty. (oranges). This is legal, since both values have units of qty. However, the label of the result must be (fruit) rather than (oranges). Otherwise, the label of the result would change if the number of apples changed to be larger than the number of oranges, resulting in changes propagating throughout the spreadsheet. This could be confusing to the user.

## 5.8. Properties of Labels

Let  $\leq_\ell$  be the partial ordering on labels as given above. Let  $\wedge$  be the operation defined for multiplication and division of labels, and  $\vee$  be the operation defined for addition and subtraction of labels.

Assume  $\Lambda$  is a label context. Define  $\Delta = \{\lambda \mid (c \in \lambda) \Rightarrow (c \in \Lambda)\}$ ; thus,  $\Delta$  is the set of all labels for the given label context  $\Lambda$ .

Claim:  $\lambda_1 \wedge \lambda_2 = \inf \{\lambda_1, \lambda_2\}$  with respect to  $\leq_\ell$ .

Proof:  $\inf \{\lambda_1, \lambda_2\} =_{\text{def}} \lambda_1 \cup \lambda_2$ . Since  $\lambda_1 \subseteq \lambda_1 \cup \lambda_2$ , we have  $\lambda_1 \wedge \lambda_2 \leq_\ell \lambda_1$ . Likewise, since  $\lambda_2 \subseteq \lambda_1 \cup \lambda_2$ , we have  $\lambda_1 \wedge \lambda_2 \leq_\ell \lambda_2$ . Suppose there existed  $\lambda$  such that  $\lambda_1 \cup \lambda_2 \leq_\ell \lambda$  but  $\lambda \leq_\ell \lambda_1$  and  $\lambda \leq_\ell \lambda_2$ . (to be completed)

Claim:  $\lambda_1 \vee \lambda_2 = \sup \{\lambda_1, \lambda_2\}$  with respect to  $\leq_\ell$ .

Proof: to be completed.

Therefore,  $(\Delta, \wedge, \vee)$  is a lattice.

## 5.9. Asymptotic Efficiency of Label Operations

To be completed.

## 6. User Interface Issues

### 6.1. Displaying Units and Labels

The system does not use labels to discover errors automatically; rather, they serve as additional information for users. This additional information can help users find errors by showing potentially unexpected properties of the results of the computations, as in the example in Figure 2. Therefore, the visual representation of labels is central in determining SLATE’s effectiveness.

Despite the additional space required for units and labels, in many cases the additional information they provide can remove the need for extraneous annotations. For example, Figures 1 and 2 express the same data, but in the second table, Figure 2 uses one fewer column because the information can be expressed with labels. Of course, the benefit is less when there are many columns.

### 6.2. Editing Units and Labels

Another central factor that determines SLATE’s effectiveness is the ease with which users may enter labels. If users choose not to enter labels, the system does not provide benefits.

One guiding principle that suggests some potential design ideas is *surprise-explain-reward* [10]. People are willing to go to some effort if they will be rewarded. For example, users may be willing to repair unit errors, since the system rewards them by evaluating their formulas. One possibility would be to give nonsense labels to values without labels. A tooltip would explain the system, and upon entering a valid label, the strange labels would disappear, potentially revealing downstream errors in the spreadsheet.

In our current implementation, users must type units and labels as text. This has the advantage of permitting users to enter data without any additional interface elements; only the keyboard is required, not both keyboard and mouse. A disadvantage, however, is that users must remember to type them correctly, and learn the syntax of units and labels.

It would be advantageous, therefore, to have a GUI tool for entering units and labels. For units, several possibilities are conceivable. Pop-up menus, either in a separate inspector window, or in cells when activated by editing the cells, could be used to select a unit. A sequence of these (one additional

menu would be displayed when previous ones were filled in), with text boxes to display exponents, could allow users to enter products of base units.

Entering labels is somewhat harder, because the context is potentially much richer. The labels context is a hierarchy, so it would be logical to display it similarly to other hierarchies that users are accustomed to managing. For example, file systems are hierarchical, so it would make sense to use a browser paradigm in which users could choose nodes to add to a label. The system would need to report an error if the user attempted to add both a node and one of its ancestors.

### 6.3. Editing the Unit and Label Contexts

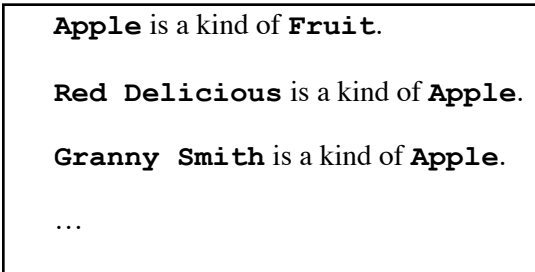
A separate issue from the interaction with the spreadsheet cells is the specification of the unit and label contexts.

Our current implementation has a static unit context. A more complete implementation should allow users to edit unit contexts, as in [2]. Although a default context containing SI, English, etc. units would suffice for most users, many users in specialized settings need unique units. One important observation, however, is that in these settings, there are frequently groups of users with the same requirements. One user should be able to create a specialized unit context, and distribute it to other users by transferring a file corresponding to the unit context.

Because the unit context is very simple, editing it is not a difficult requirement. The context consists only of a list of strings; users would simply edit the list. This requirement would be complicated by the future addition of automatic conversions or unit abbreviations. Unit conversions are complex; for example, converting US dollars to Euros requires the system to know the current exchange rate.

Interaction techniques for editing the label context are more challenging than those for the unit context, since label contexts have more complicated structure. Only a small minority of users will understand directed acyclic graphs (DAGs). One possible representation would be a list of statements, as shown in Figure 5.

For some users, a hierarchical editor, similar to some file browsers, may be appropriate. One approach would



**Apple** is a kind of **Fruit**.  
**Red Delicious** is a kind of **Apple**.  
**Granny Smith** is a kind of **Apple**.  
...

Figure 5. Users could enter the text in bold to define a label context.



have one column per level of the hierarchy; selecting an item in one column would cause the next column to display the children of the selection. The only difference between trees and DAGs in this context is the fact that items may be duplicated. Since nodes are uniquely identified by their names, it suffices to have users enter elements in multiple places in the hierarchy. Of course, such an editor would need to display errors if users ever tried to create cycles in the graph.

Just as with units, large groups of users may share a single label context, so one expert could create a context, and share it with users who do not need to understand the details of editing contexts.

## 7. Future Work

We are currently enriching SLATE with a more complete computational model and developing an appropriate treatment for labels in this setting, including conditional statements, Boolean operators, and a library of standard statistical functions. We are also adding a more complete unit system, as have been designed in other work (such as Antoniu [2] or Kennedy [3]).

In addition to enriching the language, we are designing unit and label context editors, and prototyping a method to allow users to specify units or labels for single or multiple cells simultaneously.

Displaying units and labels requires space—sometimes more than the values they correspond to. But if labels are not visible, users must explicitly make them visible to check for errors. One approach to reducing space requirements would be to use an inspector window which would display the label of the currently selected cell. Another choice would be a heuristic that would highlight cells considered most likely to contain errors; of course, this would only be an approximation of the user’s manual verification. Alternatively, labels could be displayed in tooltips when desired.

Header inference techniques from Apples and Oranges could be adopted in SLATE. Instead of requiring users to enter information about objects of measurement manually, the system could infer some information from the headers, using a similar inference algorithm.

We are designing user studies to evaluate SLATE; this is vital both for demonstrating SLATE’s ability to help users detect errors and for choosing among the many design ideas we have discussed. The system must also be tested with large contexts and data sets to show its effectiveness with large amounts of data.

## 8. Conclusions

SLATE represents a new approach to spreadsheet formula error detection. By considering objects of measurement in addition to units of measurement, it is possible to detect errors that would be hidden in other systems without presenting an onerous burden to end users. SLATE has the potential to uncover a new class of errors, and should be suitable for both small and large spreadsheets. This novel approach to error detection represents an improvement over existing techniques, which do not take objects of measurement into consideration.

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