SciSheets: Providing the Power of Programming With The Simplicity of Spreadsheets

Alicia Clark[§], Joseph L. Hellerstein[‡*]

https://www.youtube.com/watch?v=2-qCCR5r01A

Abstract—Digital spreadsheets are arguably the most pervasive environment for end user programming on the planet. Although spreadsheets simplify many calculations, they fail to address requirements for expressivity, reuse, complex data, and performance. SciSheets (from "scientific spreadsheets") is an open source project that provides novel features to address these requirements: (1) formulas can be arbitrary Python scripts as well as expressions (*formula scripts*), which addresses expressivity by allowing calculations to be written as algorithms; (2) spreadsheets can be exported as functions in a Python module (*function export*), which addresses reuse since exported codes can be reused in formulas and/or by external programs and improves performance since calculations can execute in a low overhead environment; and (3) tables can have columns that are themselves tables (*subtables*), which addresses complex data such as representing hierarchically structured data and n-to-m relationships. Our future directions include refinements to subtables, github integration, and plotting. At present, SciSheets can do robust demos, but it is not yet beta code.

Index Terms—software engineering

1. Introduction

Digital spreadsheets are the "killer app" that ushered in the PC revolution. This is largely because spreadsheets provide a conceptually simple way to do calculations that (a) closely associates data with the calculations that produce the data and (b) avoids the mental burdens of programming such as control flow, data dependencies, and data structures. Over 800M professionals author spreadsheet formulas as part of their work [MODE2017], which is over 50 times the number of software developers world wide [THIB2013].

We categorize spreadsheet users as follows:

- **Novices** want to evaluate equations, but they do not have the prior programming experience necessary to create reusable functions and longer scripts. Spreadsheet formulas work well for Novices since: (a) they can ignore data dependencies; (b) they can avoid flow control by using "copy" and "paste" for iteration; and (c) data structures are "visual" (e.g., rectangular blocks).
- **Scripters** feel comfortable with expressing calculations algorithmically using `for` and `if` statements; and they can use simple data structures such as lists and `pandas DataFrames`. However, Scripters rarely encapsulate code into functions, preferring "copy" and "paste" to get reuse.
- **Programmers** know about sophisticated data structures, modularization, reuse, and testing.

Our experience is primarily with technical users such as scientists. Most commonly, we encounter Novices and Scripters with limited prior programming experience. We do not expect these groups of users to take advantage of spreadsheet macro capabilities (e.g., Visual Basic for Microsoft Excel or AppScript in Google Sheets); we anticipate this functionality to be taken advantage of only by Programmers.

Based on this experience, we find existing spreadsheets lack several key requirements. First, they lack the **expressivity requirement** in that (a) they only permit a limited set of functions to be used in formulas (e.g., so that static dependency checking can be done); and (b) they only support formulas that are expressions, not scripts. In particular, the latter means that Scripters cannot express calculations as algorithms, and Novices cannot write linear workflows to articulate a computational recipe. A second consideration is the **reuse requirement**. Today, it is impossible to reuse spreadsheet formulas in other spreadsheet formulas or in software systems. Third, current spreadsheet systems cannot handle the **complex data requirement**, such as manipulating data that are hierarchically structured or data that have n-to-m relationships. Finally, existing spreadsheets cannot address the **performance requirement** in that spreadsheets scale poorly with the size of data and the number of formulas.

Academic computer science has recognized the growing importance of end-user programming (EUP) [BURN2009]. Even so, there is little academic literature on spreadsheets, arguably the most pervasive EUP environment on the planet. [MCLU2006] discusses object oriented spreadsheets that introduce a sophisticated object model, but the complexity of this proposal is unlikely to appeal to Novices. [JONE2003] describes a way that users can implement functions within a spreadsheet to get reuse. However, the approach imposes a significant burden on the user, and does not address reuse of formulas outside the spreadsheet environment. Industry has had significant interest in

§ Department of Mechanical Engineering, University of Washington
∗ Corresponding author: joseph.hellerstein@gmail.com
‡ eScience Institute and School of Computer Science, University of Washington. *This work was made possible by the Moore/Sloan Data Science Environments Project at the University of Washington supported by grants from the Gordon and Betty Moore Foundation (Award #3835) and the Alfred P. Sloan Foundation (Award #2013-10-29).*

innovating spreadsheets. Google Fusion Tables [GONZ2010] and the "Tables" feature of Microsoft Excel [MICROSOF] use column formulas to avoid a common source of error, copying formulas as rows are added/deleted from a table. The Pyspread [PYSPREAD] project uses Python as the formula language, but Pyspread formulas cannot be Python scripts. A more radical approach is taken by Stencila [STENCILA], a document system that provides ways to execute code that updates tables (an approach that is in the same spirit as Jupyter Notebooks [PERE2015]). Stencila supports a variety of languages including JavaScript, Python, and SQL. However, Stencila lacks features that spreadsheet users expect: (a) closely associating data with the calculations that produce the data and (b) avoiding considerations of data dependencies in calculations.

This paper introduces SciSheets [SCISHEETS], a new spreadsheet system with the objective of providing the power of programming with the simplicity of spreadsheets. The name SciSheets is a contraction of the phrase "Scientific Spreadsheet", a nod to the users who motivated the requirements that we address. That said, our target users are more broadly technical professionals who do complex calculations on structured data. We use the term **scisheet** to refer to a SciSheets spreadsheet. We note in passing that our focus for scisheets is on calculations, not document processing features such as formatting and drawing figures.

SciSheets addresses the above requirements by introducing several novel features.

- *Formula Scripts.* Scisheet formulas can be arbitrary Python scripts as well as expressions. This addresses expressivity by allowing calculations to be written as algorithms.
- *Function Export.* Scisheets can be exported as functions in a Python module. This addresses reuse since exported codes can be reused in SciSheets formulas and/or by external programs. Further, performance is improved by the export feature since calculations execute in a low overhead environment.
- *Subtables.* Tables can have columns that are themselves tables (columns within columns). This addresses the complex data requirement, such as representing hierarhically structured data and n-to-m relationships.

The remainder of the paper is organized as follows. Section 2 describes the requirements that we consider, and Section 3 details the SciSheets features that address these requirements. The design of SciSheets is discussed in Section 4, and Section 5 discusses features planned for SciSheets. Our conclusions are contained in Section 6.

2. Requirements

This section presents examples that motivate the requirements of expressivity, reuse, and complex data.

Our first example is drawn from biochemistry labs studying enzyme mediated chemical reactions. Commonly, the Michaelis-Menten [BERG2002] Model of enzyme activity is used in which there is a single chemical species, called the substrate, that interacts with the enzyme to produce a new chemical species (the product). Two properties of enzymes are of much interest: the maximum reaction rate, denoted by V_{MAX}, and the concentration K_M of substrate that achieves a reaction rate equal to half of V_{MAX}.

To perform the Michaelis-Menten analysis, laboratory data are collected for different values of the substrate concentrations S and associated reaction rates V. Then, a calculation is done to obtain the parameters V_{MAX} and K_M using the following recipe.

1) Compute $1/S$ and $1/V$, the inverses of S and V.
2) Compute the intercept and slope of the regression of $1/V$ on $1/S$.
3) Calculate V_{MAX} and K_M from the intercept and slope.

	A	B	C	D	E	F	G	H
1	S	V	INV_S	INV_V	INTERCEPT	SLOPE	V_MAX	K_M
2	0.01	0.11	100.00	9.09	4.357	0.047	0.229	0.011
3	0.05	0.19	20.00	5.26				
4	0.12	0.21	8.33	4.76				
5	0.20	0.22	5.00	4.55				
6	0.50	0.21	2.00	4.76				
7	1.00	0.24	1.00	4.17				

Fig. 1: *Data view for an Excel spreadsheet that calculates Michaelis-Menten Parameters.*

	A	B	C	D	E	F	G	H
1	S	V	INV_S	INV_V	INTERCEPT	SLOPE	V_MAX	K_M
2	0.01	0.11	=1/A2	=1/B2	=INTERCEPT(D2:D7,C2:C7)	=SLOPE(D2:D7,C2:C7)	=1/E2	=F2*G2
3	0.05	0.19	=1/A3	=1/B3				
4	0.12	0.21	=1/A4	=1/B4				
5	0.20	0.22	=1/A5	=1/B5				
6	0.50	0.21	=1/A6	=1/B6				
7	1.00	0.24	=1/A7	=1/B7				

Fig. 2: *Formulas used in Fig. 1.*

Fig. 1 shows an Excel spreadsheet that implements this recipe with column names that correspond to the variables in the recipe. Fig. 2 displays the formulas that perform these calculations. Readability can be improved by using column formulas (e.g., as in Fusion Tables). However, two problems remain. Novices cannot *explicitly* articulate the computational recipe; rather, the recipe is implicit in the order of the columns. Even more serious, there is no way to reuse these formulas in other formulas (other than error-prone copy-and-paste), and there is no way to reuse formulas in an external program.

We consider a second example to illustrate problems with handling non-trivial data relationships in spreadsheets. Fig. 3 displays data that a university might have for students in two departments in the School of Engineering, Computer Science & Engineering (CSE) and Biology. The data are organized into two tables (`CSE` and `Biology`) grouped under `Engineering`, with separate columns for student identifiers and grades. These tables are adjacent to each other to facilitate comparisons between students. However, the tables are independent of each other in

	A	B	C	D	E	F
1	Engineering					
2	CSE			Biology		
3	StudentNo	GPA		StudentNo	Track	GPA
4	C1113	3.9		B1414	A	3.4
5	C1163	3.5		B1830	B	2.3
6	C1344	3.3		B1716	C	3.7
7	C1711	3.9				
8	C1579	2.8				

Fig. 3: *Illustrative example of student grade data from two departments in the School of Engineering.* `CSE` *and* `Biology` *are separate tables that are grouped together for convenience of analysis. In existing spreadsheet systems, users cannot perform row operations such as insert, delete, and/or hide on one subtable without affecting the other subtable.*

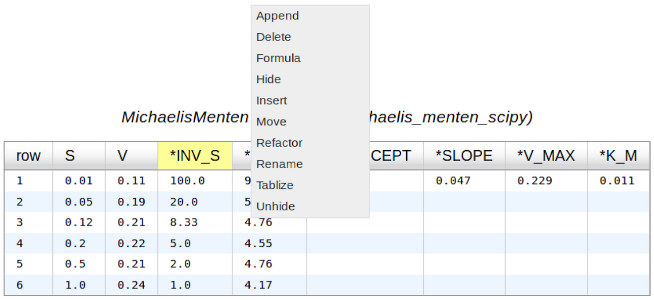


Fig. 4: *Column popup menu in a scisheet for the Michaelis-Menten calculation.*

that we should be able to insert, delete, and hide rows in one table without affecting the other table. Unfortunately, existing spreadsheet systems do not handle this well; inserting, deleting, or hiding a row in one table affects every table that overlaps that row in the spreadsheet. Note that arranging the tables vertically does not help since the problem becomes inserting, deleting, and hiding columns. We could arrange the tables in a diagonal, but this makes it difficult to make visual comparisons between tables.

3. Features

This section describes SciSheets features that address the requirements of expressivity, reuse, complex data, and performance. We begin with a discussion of the SciSheets user interface in Section 3.1. Then, Sections 3.2, 3.3, and 3.4 present formula scripts (which addresses expressivity), function export (which addresses reuse and performance), and subtables (which addresses complex data) respectively.

3.1 User Interface

Fig. 4 displays a scisheet that performs the Michaelis-Menten calculations as we did in Fig. 1. Note that columns containing a formula have a name annotated with an $\star$.

A scisheet has the familiar tabular structure of a spreadsheet. However, unlike existing spreadsheets, SciSheets knows about the **elements of a scisheet**: tables, columns, rows, and cells. In SciSheets, there are two types of columns. Data columns contain data values; subtable columns contain a table. The name of a data column is a Python variable that can be referenced in formulas. These **column variables** are `numpy Arrays`. This means that formulas can be written using column names to express vector calculation using a rich set of operators that properly handle missing data (e.g., using `NaN` values).

SciSheets users interact directly with the scisheet element appropriate for the desired action. A left click on a scisheet element results in a popup menu. For example, in Fig. 4 we see the column popup for `INV_S`. Users select an item from the popup, and this may in turn present additional menus. The popup menus for row, column, and table have common items for insert, delete, hide/unhide. Columns additionally have a formula item. The scisheet popup has items for saving and renaming the scisheet as well as undoing/redoing operations on the scisheet. The cell popup is an editor for the value in the cell.

Fig. 5 displays the results of selecting the `formula` item from the popup menu in Fig. 4 for the column `INV_S`. A simple line editor is displayed. The formula is an expression that references the column `S`.

INV_S

```
1/S
```

Fig. 5: *Formula for computing the inverse of the input value S.*

INV_V

```
import scipy.stats as ss
INV_S = np.round(1/S, 2)
INV_V = np.round(1/V, 2)
SLOPE, INTERCEPT, _, _, _ = ss.linregress(INV_S, INV_V)
V_MAX = 1/INTERCEPT
K_M = SLOPE*V_MAX
```

Fig. 6: *Formula for the complete calculation of V_{MAX} and K_M. The formula is a simple script, allowing a Novice to see exactly how the data in the scisheet are produced.*

3.2 Formula Scripts and Formula Evaluation

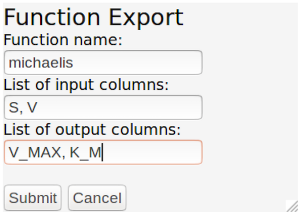
SciSheets allows formulas to be scripts with arbitrary Python statements. For example, Fig. 6 displays a script that contains the entire computational recipe for the Michaelis-Menten calculation described in Section 2. This capability greatly increases the ability of spreadsheet users to describe and document their calculations.

The formula scripts feature has a significant implication on how formulas are evaluated. Since a formula may contain arbitrary Python codes including `eval` expressions, we cannot use static dependency analysis to determine data dependencies. Thus, formula evaluation is done iteratively. But how many times must this iteration be done?

Consider an evaluation of N formula columns assuming that there are no circular references or other anomalies in the formulas. Then, at most N iterations are needed for convergence since on each iteration at least one column variable is assigned its final value. If after N iterations, there is an exception, (e.g., a column variable does not have a value assigned), this is reported to the user since there is likely an error in the formulas. Otherwise, the scisheet is updated with the new values of the column variables. Actually, we can do better than this since if the values of column variables converge after loop iteration $M < N$ (and there is no exception), then formula evaluation stops. We refer to the above workflow as the **formula evaluation loop**.

SciSheets augments the formula evaluation loop by providing users with the opportunity to specify two additional formulas. The **prologue formula** is executed once at the beginning of formula evaluation; the **epilogue formula** is executed once at the end of formula evaluation. These formulas provide a way to do high overhead operations in a one-shot manner, a feature that assists the performance requirement. For example, a user may have a prologue formula that reads a file (e.g., to initialize input values in a table) at the beginning of the calculation, and an epilogue formula that writes results at the end of the calculation. Prologue and epilogue formulas are modified through the scisheet popup menu.

At present, variable names have a global scope within the scisheet. This is often a desirable feature. For example, in Fig. 6, values computed in one column formula are assigned to another column. However, as discussed in Section 5, there are some interesting use cases for having subtable name scoping, a feature that we are implementing.



row	S	V	*INV_S	*INV_V	*INTERCEPT	*SLOPE	*V_MAX	*K_M
1	0.01	0.11	100.0	9.09	4.358	0.047	0.229	0.011
2	0.05	0.19	20.0	5.26				
3	0.12	0.21	8.33	4.76				
4	0.2	0.22	5.0	4.55				
5	0.5	0.21	2.0	4.76				
6	1.0	0.24	1.0	4.17				

Fig. 7: *Menu to export a scisheet as a function in a Python module.*

3.3. Function Export

A scisheet can be exported as a function in a Python module. This feature addresses the reuse requirement since exported codes can be used in scisheet formulas and/or external programs. The export feature also addresses the performance requirement since executing standalone code eliminates many overheads.

At first glance, it may seem that being able to export a scisheet as a function is in conflict with an appealing feature of spreadsheets--that data are closely associated with the calculations that produce the data. It is a central concern of SciSheets to preserve this feature of spreadsheets. Thus, users specify formulas for columns and/or for table prologues and epilogues without regard to how code might be exported. SciSheets automatically structures code for export.

Fig. 7 displays the scisheet popup menu for function export. The user sees a menu with entries for the function name, inputs (a list of column names), and outputs (a list of column names).

Function export produces two files. The first is the Python module containing the exported function. The second is a Python file containing a test for the exported function.

We begin with the first file. The code in this file is structured into several sections:

- Function definition and setup
- Formula evaluation
- Function close

The function definition and setup contain the function definition, imports, and the scisheet prologue formula. Note that the prologue formula is a convenient place to import Python packages.

```
# Function definition
def michaelis(S, V):
  from scisheets.core import api as api
  s = api.APIPlugin('michaelis.scish')
  s.initialize()
  _table = s.getTable()
  # Prologue
  s.controller.startBlock('Prologue')
  # Begin Prologue
  import math as mt
  import numpy as np
  from os import listdir
  from os.path import isfile, join
  import pandas as pd
  import scipy as sp
  from numpy import nan  # Must follow sympy import
  # End Prologue
  s.controller.endBlock()
```

In the above code, the imported package `scisheets.core.api` contains the SciSheets runtime. The object `s` is constructed using a serialization of the scisheet that is written at the time of function export. scisheets are serialized in a JSON format to a file that has the extension `.scish`.

We see that prologue formulas can be lengthy scripts. For example, one scisheet developed with a plant biologist has a prologue formula with over fifty statements. As such, it is essential that syntax and execution errors are localized to a line within the script. We refer to this as the **script debuggability requirement**. SciSheets handles this requirement by using the paired statements `s.controller.startBlock('Prologue')` and `s.controller.endBlock()`. These statements "bracket" the script so that if an exception occurs, SciSheets can compute the line number within the script for that exception.

Next, we consider the formula evaluation loop. Below is the code that is generated for the beginning of the loop and the evaluation of the formula for `INV_S`.

```
s.controller.initializeLoop()
while not s.controller.isTerminateLoop():
  s.controller.startAnIteration()
  # Formula evaluation blocks
  try:
    # Column INV_S
    s.controller.startBlock('INV_S')
    INV_S = 1/S
    s.controller.endBlock()
    INV_S = s.coerceValues('INV_S', INV_S)
  except Exception as exc:
    s.controller.exceptionForBlock(exc)
```

`s.controller.initializeLoop()` snapshots column variables. `s.controller.isTerminateLoop()` counts loop iterations, looks for convergence of column variables, and checks to see if the last loop iteration has an exception. Each formula column has a pair of `try` and `except` statements that execute the formula and record exceptions. Note that loop execution continues even if there is an exception for one or more formula columns. This is done to handle situations in which formula columns are *not* ordered according to their data dependencies.

Last, there is the function close. The occurrence of an exception in the formula evaluation loop causes an exception with the line number in the formula in which the (last) exception occurred. If there is no exception, then the epilogue formula is executed, and the output values of the function are returned (assuming there is no exception in the epilogue formula).

```
if s.controller.getException() is not None:
  raise Exception(s.controller.formatError(
      is_absolute_linenumber=True))
s.controller.startBlock('Epilogue')
# Epilogue (empty)
s.controller.endBlock()
return V_MAX,K_M
```

The second file produced by SciSheets function export contains test code. Test code makes use of `unittest` with a `setUp` method that assigns `self.s` the value of a SciSheets runtime object.

```
def testBasics(self):
  S = self.s.getColumnValue('S')
  V = self.s.getColumnValue('V')
  V_MAX,K_M = michaelis(S,V)
```

row	CSV_FILE	*K_M	V_MAX
1	Glu.csv	[5.179]	[0.568]
2	LL-DAP.csv	[0.929]	[23.81]
3	THDPA.csv	[0.011]	[0.229]

***Fig. 8:** A scisheet that processes many CSV files.*

K_M

```
# Compute K_M and V_MAX for each CSV file
K_M = []
V_MAX = []
for csv_file in CSV_FILE:
  df = pd.read_csv(join(PATH, csv_file))
  s_val = df['S']
  v_val = df['V']
  v_max, k_m = michaelis(s_val, v_val)
  K_M.append(k_m)
  V_MAX.append(v_max)
```

***Fig. 9:** Column formula for* `K_M` *in Fig. 8 that is a script to process a list of CSV files.*

```
self.assertTrue(
    self.s.compareToColumnValues('V_MAX', V_MAX))
self.assertTrue(
    self.s.compareToColumnValues('K_M', K_M))
```

The above test compares the results of running the exported function `michaelis` on the input columns `S` and `V` with the values of output columns `V_MAX` and `K_M`.

The combination of the features function export and formula scripts is extremely powerful. To see this, consider a common pain point with spreadsheets - doing the same computation for different data sets. For example, the Michaelis-Menten calculation in Fig. 1 needs to be done for data collected from many experiments that are stored in several comma separated variable (CSV) files. Fig. 8 displays a scisheet that does the Michaelis-Menten calculation for the list of CSV files in the column `CSV_FILE`. (This list is computed by the prologue formula based on the contents of the current directory.) Fig. 9 displays a script that reuses the `michaelis` function exported previously to compute values for `K_M` and `V_MAX`. Thus, whenever new CSV files are available, `K_M` and `V_MAX` are calculated without changing the scisheet in Fig. 8.

3.4. Subtables

Subtables provide a way for SciSheets to deal with complex data by having tables nested within tables.

	Engineering						
	[CSE]			[Biology]			
row	row	*ScholarID	GradePtAvg	row	*StudentNo	Track	GPA
	1	C1113	3.9	1	B1414	A	3.4
	2	C1163	3.5	2	B1830	B	2.3
	3	C1344	3.3	3	B1716	C	3.7
	4	C1711	3.9				
	5	C1579	2.8				

***Fig. 10:** The table* `Engineering` *has two subtables* `CSE` *and* `Biology`*. The subtables are independent of one another, which is indicated by the square brackets around their names and the presence of separate* `row` *columns.*

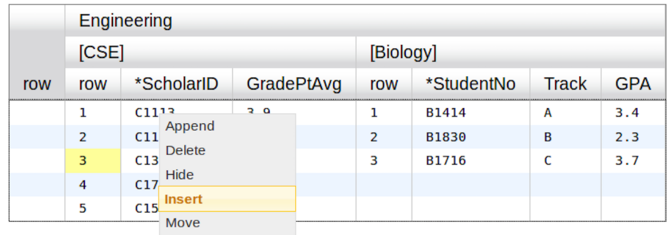


***Fig. 11:** Menu to insert a row in one subtable. The menu is accessed by left-clicking on the "3" cell in the column labelled "row" in the CSE subtable.*

	Engineering						
	[CSE]			[Biology]			
row	row	*ScholarID	GradePtAvg	row	*StudentNo	Track	GPA
	1	C1113	3.9	1	B1414	A	3.4
	2	C1163	3.5	2	B1830	B	2.3
	3			3	B1716	C	3.7
	4	C1344	3.3				
	5	C1711	3.9				
	6	C1579	2.8				

***Fig. 12:** Result of inserting a row in the* `CSE` *subtable. Note that the* `Biology` *substable is unchanged.*

We illustrate this by revisiting the example in Fig. 3. Fig. 10 displays a scisheet for these data in which `CSE` and `Biology` are independent subtables (indicated by the square brackets around the names of the subtables). Note that there is a column named `row` for each subtable since the rows of `CSE` are independent of the rows of `Biology`.

Recall that in Section 2 we could not insert a row into `CSE` without also inserting a row into `Biology`. SciSheets addresses this requirement by providing a separate row popup for each subtable. This is shown in Fig. 11 where there is a popup for row 3 of `CSE`. The result of selecting `insert` is displayed in Fig. 12. Note that the `Biology` subtable is not modified when there is an insert into `CSE`.

4. Design

SciSheets uses a client-server design. The client runs in the browser using HTML and JavaScript; the server runs Python using the Django framework [DJANGOPR]. This design provides a zero install deployment, and leverages the rapid pace of innovation in browser technologies.

Our strategy has been to limit the scope of the client code to presentation and handling end-user interactions. When the client requires data from the server to perform end-user interactions (e.g., populate a list of saved scisheets), the client uses AJAX calls. The client also makes use of several JavaScript packages including JQuery [JQUERYPR], YUI DataTable [YUIDATAT], and JQueryLinedText [JQUERYLI].

The SciSheets server handles the details of user requests, which also requires maintaining the data associated with scisheets. Fig 13 displays the core classes used in the SciSheets server. Core classes have several required methods. For example, the `copy` method makes a copy of the object for which it is invoked. To do this, the object calls the `copy` method of its parent class as well, and this is done recursively. Further, the object must call the `copy` method for core objects that are in its instance variables, such as

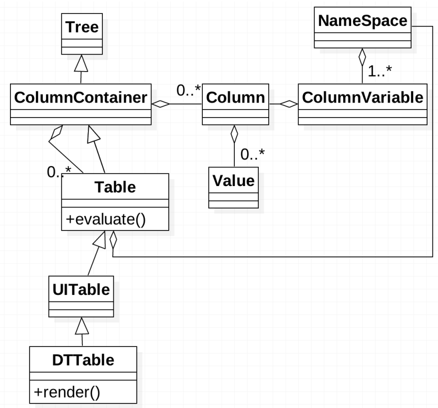


Fig. 13: *SciSheets core classes.*

ColumnContainer which has the instance variable columns that contains a list of Column objects. Other examples of required methods are isEquivalent, which tests if two objects have the same values of instance variables, and deserialize, which creates objects based on data serialized in a JSON structure.

Next, we describe the classes in Fig. 13. Tree implements a tree that is used to express hierarchical relationships such as between Table and Column objects. Tree also provides a mapping between the name of the scisheet element and the object associated with the name (e.g., to handle user requests). ColumnContainer manages a collections of Table and Column objects. Column is a container of data values. Table knows about rows, and it does formula evaluation using evaluate(). UITable handles user requests (e.g., renaming a column and inserting a row) in a way that is independent of the client implementation. DTTable provides client specific services, such as rendering tables into HTML using render().

The classes NameSpace (a Python namespace) and ColumnVariable are at the center of formula evaluation. The evaluate() method in Table generates Python code that is executed in a Python namespace. The SciSheets runtime creates an instance of ColumnVariable for each Column in the scisheet being evaluated. ColumnVariable puts the name of its corresponding Column into the namespace, and assigns to this name a numpy Array that is populated with the values of the Column.

Last, we consider performance. There are two common causes of poor performance in the current implementation of SciSheets. The first relates to data size. At present, SciSheets embeds data with the HTML document that is rendered by the browser. We will address this by downloading data on demand and caching data locally.

The second cause of poor performance is having many iterations of the formula evaluation loop. If there is more than one formula column, then the best case is to evaluate each formula column twice. The first execution produces the desired result (e.g., if the formula columns are in order of their data dependencies); the second execution confirms that the result has converged. Some efficiencies can be gained by using the prologue and epilogue features for one-shot execution of high overhead operations (e.g., file I/O). In addition, we are exploring the extent to which SciSheets can automatically detect if static dependency checking can be used so that formula evaluation is done only once.

Clearly, performance can be improved by reducing the number of formula columns since this reduces the maximum number of iterations of the formulation evaluation loop. SciSheets supports this strategy by permitting formulas to be scripts. This is a reasonable strategy for a Scripter, but it may work poorly for a Novice who is unaware of data dependencies.

5. Future Work

This section describes several features that are under development.

5.1 Subtable Name Scoping

This feature addresses the reuse requirement. Today, spreadsheet users typically employ copy-and-paste to reuse formulas. This approach has many drawbacks. First, it is error prone since there are often mistakes as to what is copied and where it is pasted. Second, fixing bugs in formulas requires repeating the same error prone copy-and-paste.

It turns out that a modest change to the subtable feature can provide a robust approach to reuse through copy-and-paste. This change is to have a subtable define a name scope. This means that the same column name can be present in two different subtables since these names are in different scopes.

We illustrate the benefits of subtable name scoping. Consider Fig. 10 with the subtables CSE and Biology. Suppose that the column GradePtAvg in CSE is renamed to GPA so that both CSE and Biology have a column named GPA. Now, consider adding the column TypicalGPA to both subtables; this column will have a formula that computes the mean value of GPA. The approach would be as follows:

1) Add the column TypicalGPA to CSE.
2) Create the formula np.mean(GPA) in TypicalGPA. This formula will compute the mean of the values of the GPA column in the CSE subtable (because of subtable name scoping).
3) Copy the column TypicalGPA to subtable Biology. Because of subtable name scoping, the formula np.mean(GPA) will reference the column GPA in Biology, and so compute the mean of the values of GPA in the Biology subtable.

Now suppose that we want to change the calculation of TypicalGPA to be the median instead of the mean. This is handled as follows:

1) The user edits the formula for the column TypicalGPA in subtable CSE, changing the formula to np.median(GPA).
2) SciSheets responds by asking if the user wants the copies of this formula to be updated as well.
3) The user answers "yes", and the formula is changed for TypicalGPA in subtable Biology.

Note that we would have the same result in the above procedure if the user had in step (1) modified the Biology subtable.

5.2 Github Integration

A common problem with spreadsheets is that calculations are difficult to reproduce because some steps are manual (e.g., menu interactions). Additionally, it can be difficult to reproduce a spreadsheet due to the presence of errors. We refer to this as the **reproducibility requirement**. Version control is an integral part of reproducibility. Today, a spreadsheet file as a whole can be

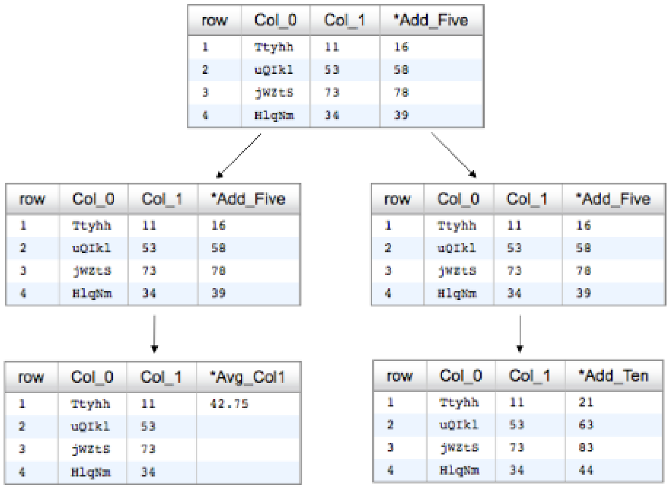


Fig. 14: Mockup showing how a scisheet can be split into two branches (e.g., for testing and/or feature exploration).

version controlled, but this granularity is too coarse. More detailed version control can be done manually. However, this is error prone, especially in a collaborative environment. One automated approach is a revision history, such as Google Sheets. However, this technique fails to record the sequence in which changes were made, by whom, and for what reason.

The method of serialization used in SciSheets lends itself well to `github` integration. Scisheets are serialized as JSON files with separate lines used for data, formulas, and structural relationships between columns, tables, and the scisheet. Although the structural relationships have a complex representation, it does seem that SciSheets can be integrated with the line oriented version control of `github`.

We are in the process of designing an integration of SciSheets with `github` that is natural for Novices and Scripters. The scope includes the following use cases:

- **Branching.** Users should be able to create branches to explore new calculations and features in a scisheet. Fig. 14 shows how a scisheet can be split into two branches. As with branching for software teams, branching with a spreadsheet will allow collaborators to work on their part of the project without affecting the work of others.
- **Merging.** Users will be able to utilize the existing `github` strategies for merging documents. In addition, we intend to develop a visual way for users to detect and resolve merge conflicts. Fig. 15 illustrates how two scisheets can be merged. Our thinking is that name conflicts will be handled in a manner similar to that used in `pandas` with `join` operations. Our implementation will likely be similar to the `nbdime` package developed for merging and differencing Jupyter notebooks [NBDIME].
- **Differencing.** Users will be able to review the history of `git commit` operations. Fig. 16 displays a mockup of a visualization of the history of a scisheet. The user will be able to select any point in history (similar to `git checkout`). This functionality will allow collaborators to gain a greater understanding of changes made.

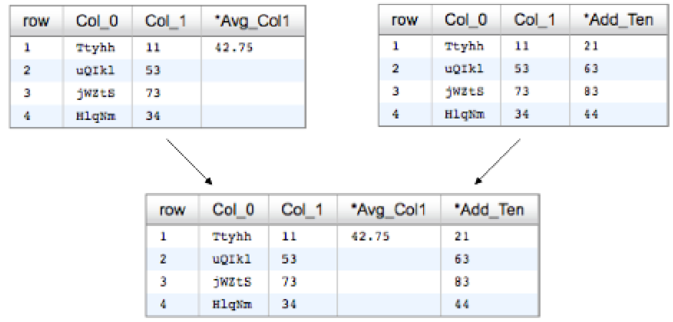


Fig. 15: Mockup displaying two scisheets can be merged (assuming no merge conflicts).

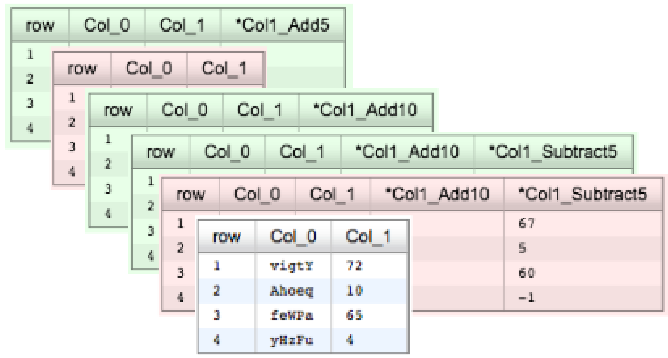


Fig. 16: Mockup visualization of the change history of a scisheet. The versions in green show when columns have been added; the versions in red show when columns have been removed.

5.3 Plotting

At present, SciSheets does not support plotting. However, there is clearly a **plotting requirement** for any reasonable spreadsheet system. Our approach to plotting will most likely be to leverage the `bokeh` package [BOKEHPRO] since it provides a convenient way to generate HTML and JavaScript for plots that can be embedded into HTML documents. Our vision is to make `plot` a function that can be used in a formula. A *plot* column will have its cells rendered as HTML.

6. Conclusions

SciSheets is a new spreadsheet system with the guiding principle of providing the power of programming with the simplicity of spreadsheets. Our target users are technical professionals who do complex calculations on structured data.

SciSheets addresses several requirements that are not handled in existing spreadsheet systems, especially the requirements of expressivity, reuse, complex data, and performance. SciSheets addresses these requirements by introducing several novel features.

- *Formula Scripts.* Scisheet formulas can be Python scripts, not just expressions. This addresses expressivity by allowing calculations to be written as algorithms.
- *Function Export.* Scisheets can be exported as functions in a Python module. This addresses reuse since exported codes can be reused in SciSheets formulas and/or by external programs. Further, performance is improved by the export feature since calculations execute in a low overhead environment.

Requirement	SciSheets Feature
• Expressivity	• Python formulas • Formula scripts
• Reuse	• Function export • *Subtable name scoping*
• Complex Data	• Subtables
• Performance	• Function export • Prologue, Epilogue • *Load data on demand* • *Conditional static dependency checking*
• Plotting	• *Embed bokeh components*
• Script Debuggability	• Localized exceptions
• Reproducibility	• `github` *integration*

TABLE 1: *Summary of requirements and SciSheets features that address these requirements. Features in italics are planned but not yet implemented.*

- *Subtables.* Tables can have columns that are themselves tables (columns within columns). This addresses the complex data requirement, such as representing n-to-m relationships.

Table 1 displays a comprehensive list of the requirements we plan to address and the corresponding SciSheets features.

One goal for SciSheets is to make users more productive with their existing workflows for developing and evaluating formulas. However, we also hope that SciSheets becomes a vehicle for elevating the skills of users, making Novices into Scripters and Scripters into Programmers.

At present, SciSheets is capable of doing robust demos. Some work remains to create a beta. We are exploring possible deployment vehicles. For example, rather than having SciSheets be a standalone tool, another possibility is integration with Jupyter notebooks.

References

[BERG2002] Berg, Jermey et al. *Biochemistry*, W H Freeman, 2002.
[BOKEHPRO] Bokeh Project. http://bokeh.pydata.org/.
[BURN2009] Burnett, M. *What is end-user software engineering and why does it matter?*, Lecture Notes in Computer Science, 2009
[DJANGOPR] Django Project. http://www.djangoproject.com.
[GONZ2010] *Google Fusion Tables: Web-Centered Data Management and Collaboration*, Hector Gonzalez et al., SIGMOD, 2010.
[JONE2003] Jones, S., Blackwell, A., and Burnett, M. i *A user-centred approach to functions in excel*, SIGPLAN Notices, 2003.
[JQUERYLI] JQueryLinedText. https://github.com/aw20/JQueryLinedText.
[JQUERYPR] JQuery Package. https://jquery.com/.
[MCCU2006] McCutchen, M., Itzhaky, S., and Jackson, D. *Object spreadsheets: a new computational model for end-user development of data-centric web applications*, Proceedings of the 2016 ACM International Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software, 2006.
[MICROSOF] Microsoft Corporation. *Overview of Excel tables*, https://support.office.com/en-us/article/Overview-of-Excel-tables-7ab0bb7d-3a9e-4b56-a3c9-6c94334e492c.
[MODE2017] *MODELOFF - Financial Modeling World Championships*, http://www.modeloff.com/the-legend/.
[NBDIME] *nbdime*, https://github.com/jupyter/nbdime.
[PERE2015] Perez, Fernando and Branger, Brian. *Project Jupyter: Computational Narratives as the Engine of Collaborative Data Science*, http://archive.iPython.org/JupyterGrantNarrative-2015.pdf.
[PYSPREAD] Manns, M. *PYSPREAD*, http://github.com/manns/pyspread.
[SCISHEET] *SciSheets*, https://github.com/ScienceStacks/SciSheets.
[STENCILA] *Stencila*, https://stenci.la/.
[THIB2013] Thibodeau, Patrick. *India to overtake U.S. on number of developers by 2017*, COMPUTERWORLD, Jul 10, 2013.
[YUIDATAT] Yahoo User Interface DataTable. https://yuilibrary.com/yui/docs/datatable/.