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

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Abstract—Digital spreadsheets are the "killer app" that ushered in the PC revolution. Today, spreadsheet users outnumber software developers by a factor of 50 or more. 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. *Formula Scripts.* Scisheet formulas can be arbitrary Python scripts as well as expressions. This addresses expressivity by allowing calculations to be written as algorithms. *Program Export.* Scisheets can be exported as standalone Python programs. 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 can execute without the overheads of the spreadsheet environment. *Subtables.* Tables can have columns that are themselves tables (columns within columns). This addresses the complex data requirement, such as representing hierarchically structured data and n-to-m relationships. 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 skill levels of users, making Novices into Scripters and Scripters into Programmers.

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 scientists, especially biologists and chemists. 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. Both restrictions limit expressivity. 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, there is the **performance requirement**, that spreadsheets scale well 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, 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 innovating spreadsheets. Google

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Fusion Tables [GONZ2010] and the "Tables" feature of Microsoft Excel ref?? 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.
- *Program Export.* Scisheets can be exported as standalone Python programs. 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 without the overheads of the spreadsheet 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 ref?? 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 concentration S and reaction rate V. Then, a calculation is done to obtain the parameters V_{MAX} and K_M using the following recipe.

	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.*

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.

Fig. 1 shows an Excel spreadsheet that implements this recipe with column names chosen to correspond to the variables in the recipe. Fig. 2 shows 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 Engineering. 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 the comparisons between students. However, the tables are independent of each other in 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; adding a row to one table affects every row in the entire spreadsheet. Note that arranging the tables vertically does not help since now the problem

	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: *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. However, it is difficult to manage them separate, such as insert, delete, and/or hide rows.*

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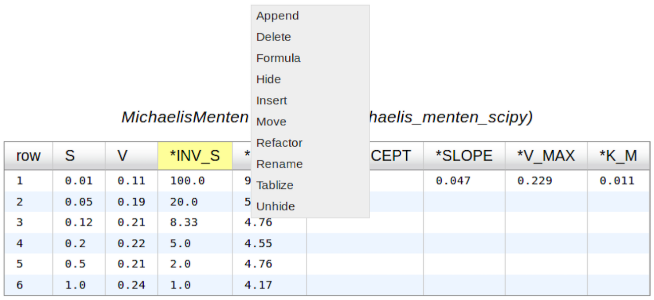

Fig. 4: *Column popup menu in a scisheet for the Michaelis-Menten calculation.*

INV_S

```
1/S
```

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

becomes adding, deleting, or 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 in turn present: formula scripts (which addresses expressivity), program export (which addresses reuse and performance), and subtables (which addresses complex data).

3.1 User Interface

Fig. 4 displays a scisheet that performs the Michaelis-Menten calculations as we did in Fig. 1. A scisheet has the familiar tabular structure of a spreadsheet. However, unlike spreadsheets, SciSheets knows about the *structure of a scisheet: scisheet (entire sheet), tables, columns, rows, and cells*. Table and column names are Python variables that the user can reference in formulas. These **Column Variables** are `numpy Arrays`. It is easy to do vector calculations on Column Variables using a rich set of operators that properly handle missing data using *nan* values.

Users interact directly with scisheet elements (instead of primarily with a menu, as is done in spreadsheet systems). A left click on a scisheet element results in a popup menu. For example, in Fig. 4 we see the column popup for the column `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 submenu resulting from 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 Variable `S`. A column that contains a formula has its name annotated with an $\star$.

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. Note that the formula assigns values to other columns.*

3.2 Formula Scripts

SciSheets allows formulas to be scripts. 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.

At this point, we elaborate briefly on how formula evaluation is done in SciSheets. Since a formula may contain arbitrary Python expressions 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 inherent anomalies in the formulas. Then, at most N iterations are needed to converge since on each iteration at least one Column Variable is assigned its 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 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 this 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 and so providing another feature related to the Performance requirement. For example, a user may have 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.

3.3. Program Export

A scisheet can be executed as a standalone program or as a function in a python module. The feature addresses the Reuse requirement since exported programs can be used in scisheet formulas and/or external programs. The export feature also addresses the Performance requirement since executing standalone code eliminates the overheads of the spreadsheet environment.

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

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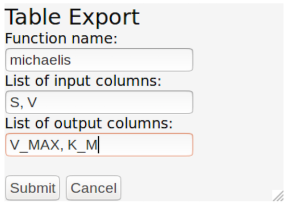

MichaelisMenten (Table File: michaelis_menten_demo)

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	8.33333333333	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 table as a standalone python program.*

Program 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 (a script consisting of imports).

```
# 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, there is an import of `api` from `scisheets.core`. `api` is the SciSheets runtime. The API object `s` is constructed from the exported scisheet that is serialized in a JSON format with extension `.scish`.

This code points to a somewhat subtle requirement that SciSheets addresses. We refer to this as the **Script Debuggability Requirement**, a requirement that arises because allowing a formula to be a script means that errors must be localized to a line within the formula. SciSheets handles this through the use of the paired statements `s.controller.startBlock('Prologue')` and `s.controller.endBlock()`. These statements allow the SciSheets API as to identify which formula is being executed so that formula errors can be localized to a particular line.

Next, we consider the formula evaluation loop.

```
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. For each formula column, there is a `try except` block that informs the API as to the formula being executed, executes the formula, and records any exception. Note that loop execution continues even if there is an execution for a formula column; this is essential if 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 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
s.controller.endBlock()

return V_MAX,K_M
```

The second file produced by program export is a test file. The test code makes use of `unittest` with a `setUp` method that assigns `self.s` the value of an API object. The test is to compare the results of running the exported function on columns in the scisheet that are input to the function with the values of columns that are outputs from the function.

```
def testBasics(self):
  # Assign column values to program variables.
  S = self.s.getColumnValue('S')
  V = self.s.getColumnValue('V')
  V_MAX,K_M = michaelis(S,V)
  self.assertTrue(
      self.s.compareToColumnValues('V_MAX', V_MAX))
  self.assertTrue(
      self.s.compareToColumnValues('K_M', K_M))
```

The combination of the program export and formula script features is very powerful. For example, the `michaelis` function exported in Fig. 8 reuses the `michaelis` function to process a list of files. Fig. 9 displays the column formula for `K_M`.

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.*

3.4. Subtables

Subtables provide a way for SciSheets to deal with complex data. This feature allows the user to nest a table within another table.

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.*

	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: A table with two subtables. Subtables CSE and Biology can be manipulated separately.

We illustrate this by revisiting the example in Fig. 3. Fig. 10 displays a scisheet for these data that is similar to Fig. 3. However, unlike traditional spreadsheet programs, *SciSheets treats "CSE" and "Biology" as independent tables.*

To see this, 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 row popup for each table. 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.

	Engineering						
	[CSE]			[Biology]			
row	row	*ScholarID	GradePtAvg	row	*StudentNo	Track	GPA
	1	C1113	3.9	1	B1414	A	3.4
	2	C11		2	B1830	B	2.3
	3	C13		3	B1716	C	3.7
	4	C17					
	5	C15					

Append
Delete
Hide
Insert
Move

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 one subtable. Note that a row is inserted in the CSE subtable without affecting the Biology substable.

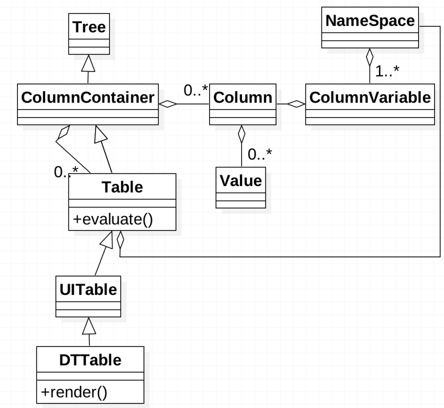

Fig. 13: SciSheets core classes.

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 ref??. This design provides a zero install deployment and leverages the rapid innovation of browser technologies.

Our strategy has been to limit the scope of the client code to presentation and handling end-user interactions. In some cases, the client requires data from the server to perform an end-user interaction (e.g., populate a list of saved scisheets). In these cases, the client interacts with the server via AJAX calls. The client makes use of several JavaScript packages including JQuery, YUI DataTable, and JQueryLinedText.

The SciSheets server handles the details of 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. One example of this is the `copy` method. This method makes a copy of the object for which it is invoked. To do this, the object calls the `copy` method for its parent class as well (which happens recursively). Further, the object must call the `copy` method for core objects that are instance variables. For example, `ColumnContainer` objects have an 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.

We now describe the responsibility of the classes in the `Tree` hierarchy 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

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an instance of a `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). Also, 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 Subtables with Scoping

This feature addresses the reuse requirement. Today, spreadsheet users typically use copy-and-paste to reuse formulas. This approach suffers from many problems. 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 copy-and-paste, another error prone process.

It turns out that a modest change to the subtable feature can provide a robust approach to reuse through copy-and-paste. The feature is to have subtables define a name scope. To see this, consider Fig. 10 with the subtables `CSE` and `Biology`. Suppose further that these subtables both have a column named `GPA`, and we want to add the column `TypicalGPA` to both subtables. The approach would be as follows:

1. Add the column `TypicalGPA` to `CSE`.
2. Create the formula `np.mean(GPA)` in `TypicalGPA`.
3. Copy the column `TypicalGPA` to subtable `Biology` Since the subtable scope is local, the formula `np.mean(GPA)` will reference the column `GPA` in `Biology`.

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`.

5.2 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 be to leverage the bokeh package ref?? 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.

5.3 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 version controlled, but this granularity is too course. More detailed version control can be done manually. However, this is error prone, and it is very difficult to keep current (a considerably problem 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 a user friendly integration of SciSheets with github. The scope here includes the following use cases:

- **Branching.** Users should be able to create branches to explore new calculations and also features in a scisheet. Fig. 14 shows how a Scisheet can be split into two separate branches. As with branching for software teams, branching with a spreadsheet will allow collaborators to work on their part of the project without worrying about affecting the work of others.
- **Merging.** Users will be able to utilize the existing github strategies for merging two documents. In addition to having a code based implementation to solve merge conflicts, we intend to develop a visual way for users to approve or deny merge conflicts within the Scisheet itself. Fig. 15 shows how two Scisheets can be merged into an individual spreadsheet. This implementation will be similar to the *nbdime* package developed for merging and differcing Jupyter notebooks [NBDIME].
- **Differencing.** Users will be able to look through the history of git commits to explore previous changes. Fig. 16 shows a visual example of the history of a SciSheet. The user will be able to select any point in history to further explore the history (similar to `git checkout`).

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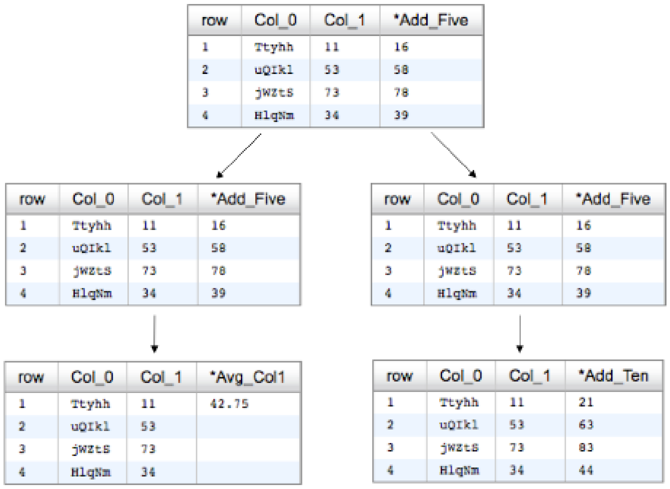

Fig. 14: Diagram showing how a scisheet can be split into two separate branches for testing code features.

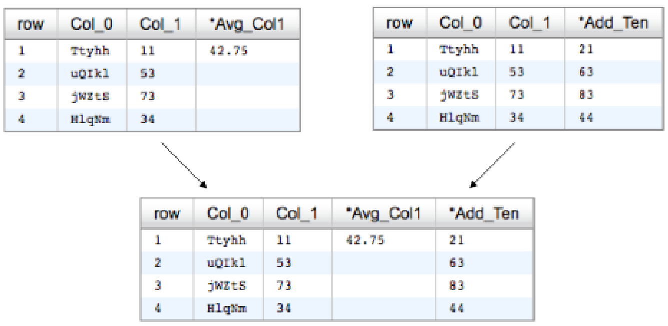

Fig. 15: Diagram showing how two scisheets will be merged (assuming no merge conflicts).

This functionality will allow collaborators to gain a greater understanding of changes made to the spreadsheet and potentially reduce duplicate implementations of certain formulas.

6. Conclusions

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

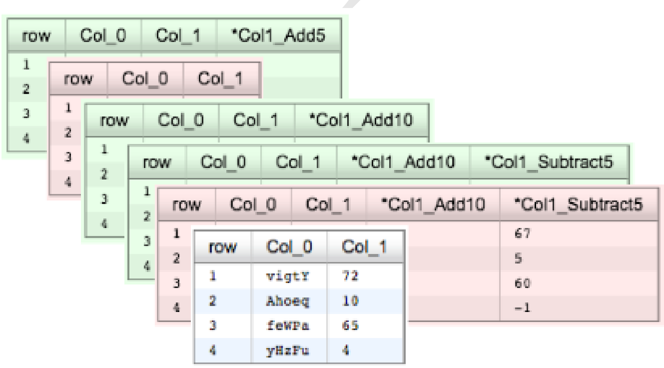

Fig. 16: Diagram showing a visual history of the SciSheet.

Requirement	SciSheets Feature
• Expressivity	• Python formulas • Formula scripts
• Reuse	• Program export • *Subtables with Scoping*
• Complex Data	• Subtables
• Performance	• Progam 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.

SciSheets addresses several requirements that are not handled well 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.
- *Program Export.* Scisheets can be exported as standalone Python programs. This addresses reuse since exported spreadsheets can be reused in SciSheets formulas and/or by external programs (e.g., written by Programmers). Further, performance is improved by the export feature since calculations can execute without the overheads of the spreadsheet environment.
- *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 skill levels of users, making Novices into Scripters and Scripters into Programmers.

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

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