

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

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Abstract—Short abstract.

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. Estimates suggest that over 800M professionals author spreadsheet formulas as part of their work [MODE2017], which is about 50 times the number of software developers world wide [Thib2013].

We categorize spreadsheet users as follows:

- **Calcers** want to evaluate equations. Spreadsheet formulas work well for Calcers 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` (which are like spreadsheets). However, they rarely encapsulate code into functions, preferring to copy and paste code 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 Calcers and Scripters. Only Programmers take advantage of spreadsheet macro capabilities (e.g., Visual Basic for Microsoft Excel or AppScript in Google Sheets).

Based on this experience, we find existing spreadsheets lack several key requirements. The first requirement is **Expressivity**. Existing spreadsheets only support formulas that are expressions, not scripts. This is significant limitation for Scripters

who often want to express calculations as algorithms. It is also a burden for Calcers who want to write linear workflows to articulate a computational recipe, a kind a computational laboratory notebook. A second requirement not addressed in today's spreadsheets is **Reuse**. Specifically, it is impossible to reuse spreadsheet formulas in other spreadsheet formulas or in software systems. A third requirement that is missing from existing spreadsheets is handling **Complex Data**. For example, today's spreadsheets make it extremely difficult to manipulate hierarchically structured data and n-to-m relationships. A final requirement we consider is **Performance**. A common complaint is 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. [MCLU2006] discusses object oriented spreadsheets that introduces a sophisticated object model but fails to recognize the requirements of Calcers to have a simple way to evaluate equations. [JONE2003] describes a way that users can implement functions within a spreadsheet to get reuse, but the approach requires considerable user effort and does not address reuse of spreadsheet formulas in a larger software system. Outside of academia there has been significant interest in innovating spreadsheets. Google Fusion Tables [Gonz2010] and the "Tables" feature of Microsoft Excel ref?? use column formulas to avoid a common source of errors, the need to copy formulas as rows are added/deleted from a table. The Pyspread [PySpread] project uses Python as the formula language, which gives formulas access to thousands of Python packages. 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 delivering 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

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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 Python scripts, not just expressions. This addresses the expressivity requirement since calculations can be expressed as algorithms.
- **Program Export.** Scisheets can be exported as standalone Python programs. This addresses the reuse requirement 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.

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 presented 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 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.

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. Calcers cannot make an explicit statement

	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.

of the computational recipe; rather, it 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 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. The data are organized into two tables (CSE and Biology) grouped under the School of 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 in that adding a row to one table affects all tables on that row in the sheet. Note that arranging the tables vertically does not help since now the problem 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 becomes.)

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

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

row	S	V	*INV_S	haelis_menten_scipy
1	0.01	0.11	100.0	
2	0.05	0.19	20.0	
3	0.12	0.21	8.33	
4	0.2	0.22	5.0	
5	0.5	0.21	2.0	
6	1.0	0.24	1.0	

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 .

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 pandas 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 `*`.

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.

INV_V
<pre> 1 import scipy.stats as ss 2 INV_S = np.round(1/S, 2) 3 INV_V = np.round(1/V, 2) 4 SLOPE, INTERCEPT, _, _ = ss.linregress(INV_S, INV_V) 5 V_MAX = 1/INTERCEPT 6 K_M = SLOPE*V_MAX 7 </pre>

Fig. 6: Formula for the complete calculation of V_{MAX} and K_M . The formula is a simple script, allowing a Calcer to see exactly how the data in the scisheet are produced. Note that the formula assigns values to other columns.

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.

SciSheets augments formula evaluation 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 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 code standalone 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).

Program export produces two files. The first is the python module containing the exported function. The second is a

Table Export

Function name:

List of input columns:

List of output columns:

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.

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 contains 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 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 formula evaluation.

```
# Loop initialization
s.controller.initializeLoop()
```

row	CSV_FILE	*K_M	V_MAX
1	Glucose.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.

```
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 had 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. Here, the loop termination condition is checked. The occurrence of an exception formula evaluation 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.

```
# Close of function
s.controller.endAnIteration()

if s.controller.getException() is not None:
    raise Exception(s.controller.formatError(
        is_absolute_line_number=True))

s.controller.startBlock('Epilogue')
# Epilogue
s.controller.endBlock()

return V_MAX, K_M
```

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


```

K_M
1 # Compute K_M and V_MAX for each CSV file
2 K_M = []
3 V_MAX = []
4 for csv_file in CSV_FILE:
5     df = pd.read_csv(join(PATH, csv_file))
6     s_val = df['S']
7     v_val = df['V']
8     v_max, k_m = michaelis(s_val, v_val)
9     K_M.append(k_m)
10    V_MAX.append(v_max)
11

```

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.

to process a list of files. Fig. 9 displays the column formula for K_M .

3.4. Subtables

Subtables provide a way for SciSheets to deal with complex data. This feature allows for having tables nested within a table.

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, there is an importance. *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. SciSheet 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.

4. Design

SciSheets uses a client-server design. The client runs in the browser using HTML and JavaScript; the server runs Python

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					

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 subtable.

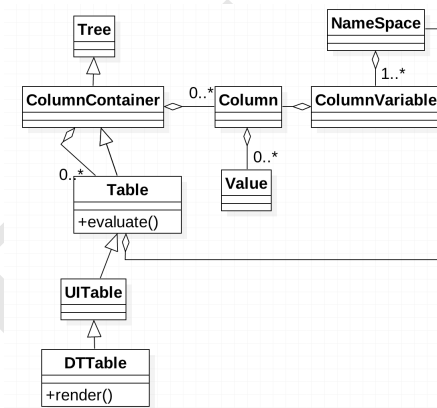


Fig. 13: SciSheets core classes.

using the Django framework. This design provides benefits, especially zero install deployment and leverage the rapid pace of innovation of browser technologies.

Our strategy has been to limit the scope of the client codes to presentation and handling end-user interactions. The client's scisheets is limited to handling interactions to recognize which scisheet element is clicked and to providing menus in response to clicks. When additional data are required to populate a menu (e.g., the scisheet "open" item), the client uses AJAX to obtain information from the server. In general, AJAX calls specify a scisheet element (e.g., column), its name, an action to perform (e.g., rename), and arguments.

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 backend.

1. Common methods for classes: copy, isEquivalent, getSerializationDict, deserialize
2. coerce method for value
3. recursive operation of copy, isEquivalent, getSerializationDict, deserialize
4. What each level in the hierarchy does

Last, we consider performance. Our experience is that there are two common causes of poor performance in our current implementation of SciSheets. The first relates to data size since, at present, SciSheets embeds data with the HTML document that is rendered by the browser. We expect to address this by implementing a feature whereby data are downloaded on demand and cached 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 (which is possible 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 detect automatically when static dependency checking is possible 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 Calcer who is unaware of data dependencies.

5. Future Directions

5.1 Subtables with Scoping

1. Approach to reuse

5.2 Plotting

- **Plotting** requirement.

5.3 Multiple Languages

5.4 Github Integration

- **Reproducibility** requirement.
 - Why version control
 - Structure of the serialization file
 - User interface for version control

6. Conclusions

We developed SciSheets to address deficiencies in existing spreadsheet systems.

1. Discuss entries in table. For now, performance is not evaluated.
2. SciSheets seeks to improve the programming skills of its users. It is hoped that Calcers will start using scripts, and that Scripters will gain better insight into modularization and testing.

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Requirement	SciSheets Feature
• Expressivity	<ul style="list-style-type: none"> • Python formulas • Formula scripts
• Reuse	<ul style="list-style-type: none"> • Program export • <i>Subtables with Scoping</i>
• Complex Data	<ul style="list-style-type: none"> • Subtables
• Performance	<ul style="list-style-type: none"> • Program export • Prologue, Epilogue • <i>Load data on demand</i> • <i>Conditional static dependency checking</i>
• Plotting	<ul style="list-style-type: none"> • <i>Embed bokeh components</i>
• Script Debuggability	<ul style="list-style-type: none"> • Localized exceptions
• Reproducibility	<ul style="list-style-type: none"> • <i>github integration</i>

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

- [PySpread] Manns, M. *PYSPREAD*, <http://github.com/manns/pyspread>.
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- [SciSheet] SciSheets, <https://github.com/ScienceStacks/SciSheets>.