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 that despite the appeal of spreadsheets, especially to Calcers and Scripters, existing spreadsheets lack several key requirements:

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- **Expressivity**: The expressivity of formulas is limited because formulas are restricted to being expressions, not scripts. This means that calculations cannot be written as algorithms, a key consideration for Scripters. It also means that Calcers cannot write a step-by-step recipe for how data are produced.
- **Reuse**: It is impossible to reuse spreadsheet formulas in other formulas or in software systems.
- **Complex Data**: It remains burdensome to deal with complex data relationships in spreadsheets, such as hierarchically structured data.
- **Performance**: Very little has been done to address the performance problems that occur as spreadsheets scale.

Academic computer science has recognized the growing importance of end-user programming (EUP) [BURN2009]. Even though spreadsheets are arguably the most pervasiveness form of EUP, there is a virtual absence of academic literature that addresses the shortcomings of spreadsheets. 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 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.

- *Scisheet formulas can be Python scripts, not just expressions.* This addresses the expressivity requirement since calculations can be expressed as algorithms.
- *Scisheet 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 feaure since calculations can execute without the overheads of the spreadsheet environment.
- *Tables can have nested columns (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 motivates through examples the requirements of expressivity, reuse, and complex data.

Our first example is relates to a procedure done in biochemistry labs studying enzyme mediated 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 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}. 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.

Fig. 1 shows an Excel spreadsheet displaying values of :math:V_{MAX} and K_M for a Michaelis-Menten calculation. The procedure is:

- Compute the inverse of S and V, the columns `INV_S` and `INV_V`.
- Compute the intercept and slope of the regression of `INV_V` on `INV_S`, the columns `INTERCEPT` and `SLOPE`.
- Calculate the columns `V_MAX` and `K_M` from `INTERCEPT` and `SLOPE`.

Fig. 3 shows the formulas that perform these calculations.

1. Expressivity and Reuse
   a. Background. Common processing of biochemical assays to compute key characteristics of enzymes
   b. Requirements
      a.) *Expressivity*: limited ability specify calculations as expressions b.) *Reuse*: Cannot reuse

	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.*

(robustly) formulas in other spreadsheets or in software systems

2. Complex Data
   a. Background. Multiple departments in the school of engineering, keeping records in slightly different ways.
   b. Requirements
      a) *Complex data*: Cannot easily manipulate complex data, such as nested tables. Examples include of manipulations: View data side-by-side, but still manage as separate tables in terms of insert/delete.

3. Features

3.1 UI Structure

1. Basics
   a. Elements - sheet, tables, columns, rows, cells (Fig)
   b. Row column - unique ID (name) for row
   c. Common popup menus for sheet, table, column, row: insert, delete, hide/unhide, rename (for row, moves the row)
   d. Cell - edit
   e. Column: formula
   f. Table: prologue, epilogue
   g. scisheet: saveas, undo/redo, export
   h. Column names are pandas array. Referred to as **Column Variables**. Means that vector oper-

	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.*

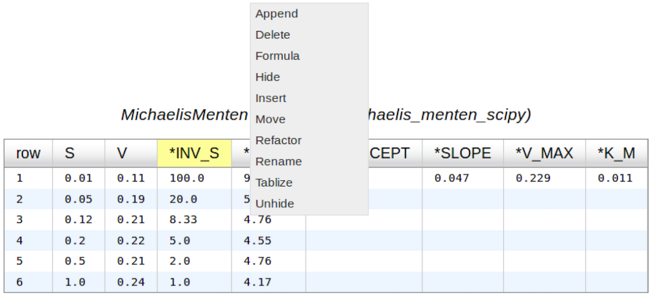


Fig. 4: *Column popup menu in a scisheet for the Michaelis-Menten calculation.*

INV_S

```
1/S
```

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

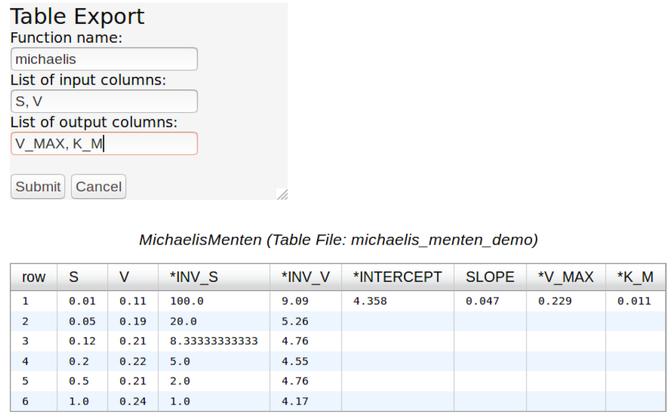
ations are supported, natural for Calcer. Also, handles missing data.

2. Challenges with formula evaluation because of arbitrary code.
3. Workflow for table evaluation
   a. Prolog - initialize Column Variables from the table. If there is no exception, then control continues to formula evaluation. Otherwise an exception is raised.
   b. Formula evaluation loop. Evaluate each column formula until one of the following holds:
      a) All Column Variables have the same value in two successive iterations of the formula evaluation loop and there is no exception.
      b) A specified number of iterations has occurred. The number of iterations is equal to the number of formula columns. If there is no exception, then control continues to the Epilogue. Otherwise an exception is raised.
   c. Epilogue. Evaluate the Epilogue formula. If no exception occurs, update the column values.

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 Calcer to see exactly how the data in the scisheet are produced.*



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.*

	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. 8: *A table with two subtables. Subtables CSE and Biology can be manipulated separately, providing a way to express n-to-m relationships.*

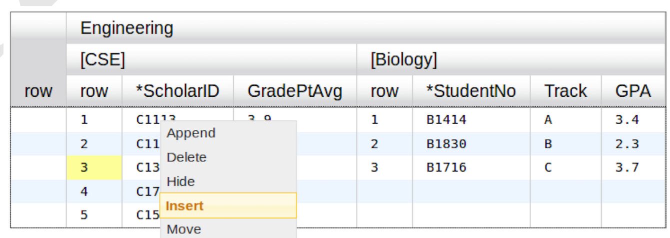


Fig. 9: *Menu to insert a row in one subtable. The menu was accessed by left-clicking on the "3" cell in the column labelled "row" in the CSE subtable.*

	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. 10: *Result of inserting a row in one subtable. Note that a row inserted in the CSE subtable without affecting the Biology substable.*

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. 11: *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. 12: *Column formula that is a script to process CSV files.*

3.2 Formulas Can Be Scripts

3.3. Program Export

3.4. Hierarchical Tables

4. Design

To enable a zero-install deployment and leverage the rapid pace of UI innovation happening with web technologies, SciSheets is a client-server application in which the front end uses HTML and Javascript; tables are rendered using YUI DataTables ref??. The backend handles the bulk of the computing tasks (e.g., formula evaluation). We connect the frontend and backend using Django ref??.

Fig 13 displays the relationships between core classes used in the SciSheets backend.

The use casses create the following requirements: (a) SciSheets must perform calculations without prior knowledge of data dependencies between columns; and (b) column formulas may be arbitrary Python scripts. The implies that *SciSheets cannot use a static analysis to discover data dependencies between columns* (as is possible in a traditional spreadsheet). To see the issue here, note that a formula may contain an `eval` statement on a string variable whose value cannot be determined until runtime. Another example is that a formula may call an external function that changes values in columns.

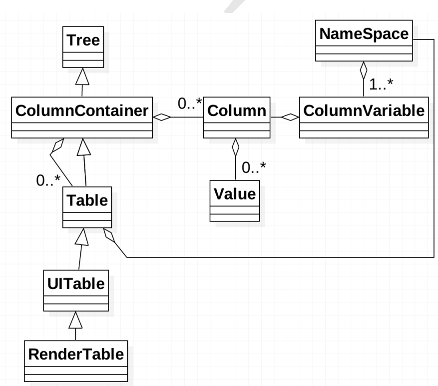


Fig. 13: *SciSheets core classes.*

A second implication follows from (b); this relates to debuggability. Specifically, since a formula may be a script consisting of many lines, syntax errors and exceptions must localize the problem to a line within the script. We refer to this as the **Script Debuggability Requirement**.

We begin with our approach to handling data dependencies. Our solution is ...

- Use term "formula evaluation loop"
- Calculation workflow

Concern (2), localizing errors, seques into a broader discussion of how spreadsheets are executed. This must be done in a way so that the column formulas run in a standalone program.

```
# 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()


#
  # Loop initialization
  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)

    try:
      # Column INV_V
      s.controller.startBlock('INV_V')
      INV_V = np.round(1/V,2)
      s.controller.endBlock()
      INV_V = s.coerceValues('INV_V', INV_V)
    except Exception as exc:
      s.controller.exceptionForBlock(exc)

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

  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
```

Tests

```
from scisheets.core import api as api
from michaelis import michaelis
import unittest

#############################
# Tests
#############################
# pylint: disable=W0212,C0111,R0904
class Testmichaelis(unittest.TestCase):

  def setUp(self):
    from scisheets.core import api as api
    self.s = api.APIPlugin('michaelis.scish')
    self.s.initialize()
    _table = self.s.getTable()

  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))

if __name__ == '__main__':
  unittest.main()
```

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 since, at present, SciSheets embeds data with the HTML document that is rendered by the browser. We expect to address this by implementing a feaure 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

- Hierarchical tables with local scopes provides another approach to reuse.
- Graphics
- Multiple languages
- Github integration
  - Why version control
  - Structure of the serialization file
  - User interface for version control

Requirement	SciSheets Feature
• Expressivity	• Python formulas • Formula scripts
• Reuse	• Program export • *Hierarchical tables with local scopes*
• Complex Data	• Hierarchical tables
• Performance	• Progam export • Prologue, Epilogue • *Load data on demand* • *Conditional static dependency checking*
• Plotting	• *Embed bokeh components*
• Script Debuggablity	• 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.*

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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