



# PECOS

Predictive Engineering and Computational Sciences

## Tools and Techniques for Scientific Software Verification (using Manufactured Solutions)

Nicholas Malaya & Chris Simmons

Center for Predictive Engineering and Computational Sciences (PECOS)

Institute for Computational Engineering and Sciences (ICES)

The University of Texas at Austin

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# Outline

This talk is online:

<https://github.com/manufactured-solutions/presentations/>

## Lecture

- Motivation for Verification
- Introduction to the Method of Manufactured Solutions
- Creating Manufactured Solutions
- The MASA Library

# Scientific Computing In Practice

Numerical simulations have a broad range of applicability

- Computer Aided Design (e.g. Boeing 787)
- Human treatment and drug discovery
- Societal impact (global warming yes/no?)
- Disaster recovery and prediction (e.g. earthquakes, hurricanes, storm surges)
- Helping to further our understanding of the physical world (material science, supernovae)
- *Possibly getting you a degree...*

# Computer Modeling and Simulation

## Most types of programming:

- Some errors are tolerable, some physics are negotiable (e.g. shaders, rendering)
- Speed is negotiable
- Often has to be pretty or easy to use, or both

## Scientific and Technical Computing:

- You have to be correct (or at least quantifiably wrong)
- We often don't know the "correct" answer
- Sometimes we cannot make new experiments (e.g. NNSA stockpile stewardship)
- Needs to be fast (*think hurricane weather prediction*)
- Software does not need to be easy to use

# What is verification?

Reality



↓ (Validation)

Mathematical Model

$$\frac{d^2x(t)}{dt^2} = \frac{F}{M}$$

↓ (Verification)

Numerical Representation

$$\frac{d^2x}{dt^2} = f''(t) = \frac{f(t+h) - 2f(t) + f(t-h)}{h^2} + ?$$

# Why Verify?

## Reinhart and Kenneth S. Rogoff: Growth in a Time of Debt, 2010

- “Our main result is that whereas the link between growth and debt seems relatively weak at normal debt levels, median growth rates for countries with public debt over roughly 90 percent of GDP are about one percent lower than otherwise”
- Dataset: “inflation and GDP growth across varying levels of debt for 20 advanced countries over the period 1946 through 2009”
- Rogoff testified in front of the Senate Budget Committee

## Inform Decision Makers

- France: 30 Billion Euros in Austerity Measures
- England: 11.5 Billion Pounds in Austerity Measures
- “Spain’s national budget cuts of almost 14 percent and regional budget cuts of up to 10 percent in health and social services”

# Verification Failure

## Excel Error!

- “Instead of AVERAGE(L30:L49), AVERAGE(L30:L44) was used.”
- When corrected, GDP/DEBT ratios above 90% had growth of 2.2%



# JP Morgan needs more verification

## Estimating risk with computer models

- JPMorgan CIO needed a new value-at-risk (VaR) model for the synthetic credit portfolio
- "London-based quantitative expert, mathematician and model developer" was dispatched
- The model underestimated downside in portfolio
- Resulted in \$6 billion in losses and another \$600 million in fines.

## What went wrong?

- After subtracting the old rate from the new rate, the spreadsheet divided by their sum instead of their average
- The errors stemmed from a combination of copy-paste mistakes and a faulty equation created to crunch the numbers.
- This error had the effect of muting volatility by a factor of two!!

Surely those were isolated events, right?

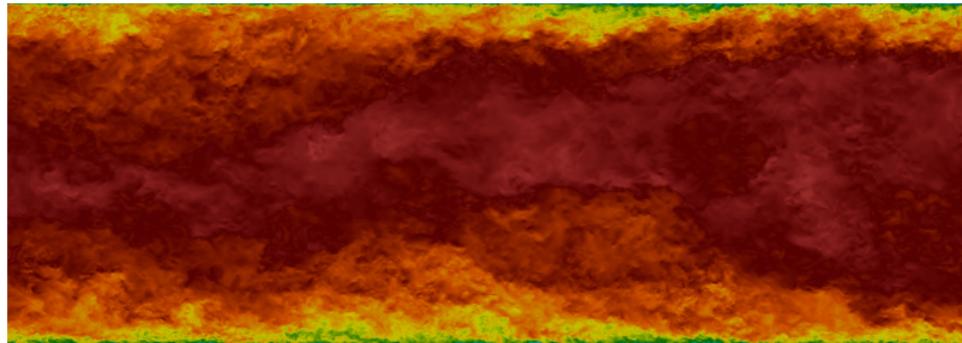
## Other examples

- Mars Surveyor (metric versus english units)
- Sleipner A - North Sea Oil Platform Collapse ("serious error in the finite element analysis")
- Therac-25 (overdosed more than two-dozen patients with gamma radiation)
- Patriot missile mistiming (only off by one third of a second!)

# Direct Numerical Simulations

## Physics Simulation

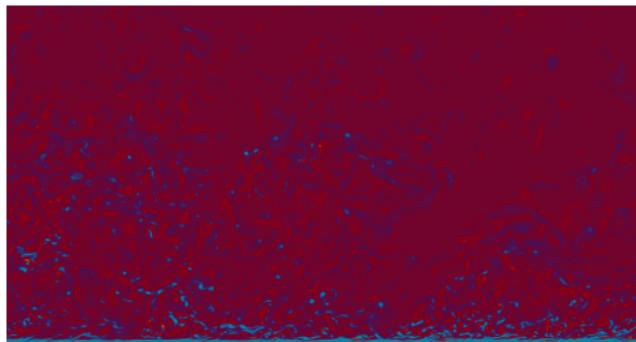
- 225 Billion Degrees of Freedom
- 524,288 Processing Cores
- 275 Million Compute Hours
- Indistinguishable from physical experiments
- **Are we confident in our predictions?**



# Direct Numerical Simulations

It's not you, it's me.

- “We have released Mira for use. However, service is degraded. Several racks (1024 nodes each) remain offline, and the system will have a high risk of hardware errors.”
- “A new efix was installed on Mira and Cetus which contains fixes and performance enhancements for the BG/Q MPI and PAMI packages. All users are strongly advised to recompile and relink their code.”
- **Are we STILL confident in our predictions?**



# Verification

## Verification of Scientific Software

- Verification ensures that the outputs of a computation accurately reflect the solution of the mathematical models.

## Code Verification

- Ensuring that the code used in the simulation correctly implements the intended numerical discretization of the model.
  - ▶ This concept is *\*not\** unique to Scientific Software

## Solution Verification

- Are the errors from the numerical discretization sufficiently small?
- Is the convergence rate consistent with the numerical scheme?

# Solution Verification Methods

## Method of Exact Solutions

- Numerically solve the governing equations for which the solution can be determined analytically.

## MMS

- Often, analytical solutions either:
  - ▶ Do not exist (Navier-Stokes)
  - ▶ Do not fully exercise equations (e.g. a symmetric solution, nonlinearities)
- Alleviate this using Method of Manufactured Solutions (MMS)
  - ▶ Simply put, we “create” our own solutions

# Manufactured solution to Laplace's Equation

Laplace's Equation:

$$\nabla^2 \phi = 0$$

In two dimensions:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

“Manufacture” a solution, with two constants:

$$\phi(x, y) = (\textcolor{red}{Ly} - y)^2(\textcolor{red}{Ly} + y)^2 + (\textcolor{red}{Lx} - x)^2(\textcolor{red}{Lx} + x)^2$$

## Calculating the Source Term

We insert our manufactured solution back into the governing equations:

$$\frac{\partial^2((Lx - x)^2(Lx + x)^2)}{\partial x^2} + \frac{\partial^2((Ly - y)^2(Ly + y)^2)}{\partial y^2} = 0$$

$$\begin{aligned} &= 2(Lx - x)^2 - 8(Lx - x)(Lx + x) + 2(Lx + x)^2 \\ &+ 2(Ly - y)^2 - 8(Ly - y)(Ly + y) + 2(Ly + y)^2 \\ &\neq 0 \end{aligned}$$

This does not satisfy Laplace's Equation!

To balance the equation, add the residual to the RHS as a source term.

## Example Verification Use Case

To solve Laplace's Equation numerically, we need a discretization scheme.

Let's use a 2nd order finite central difference:

$$\phi_i'' \approx \frac{\phi_{i+1} - 2\phi_i + \phi_{i-1}}{h^2} + \mathcal{O}(h^2)$$

This requires solving the implicit system of equations:

$$A\vec{\phi} = \textcolor{red}{f}$$

You can use your favorite linear solver (e.g. PETSc) to solve the system.

# Problem: Solve 2D Laplacian using Finite-Differencing

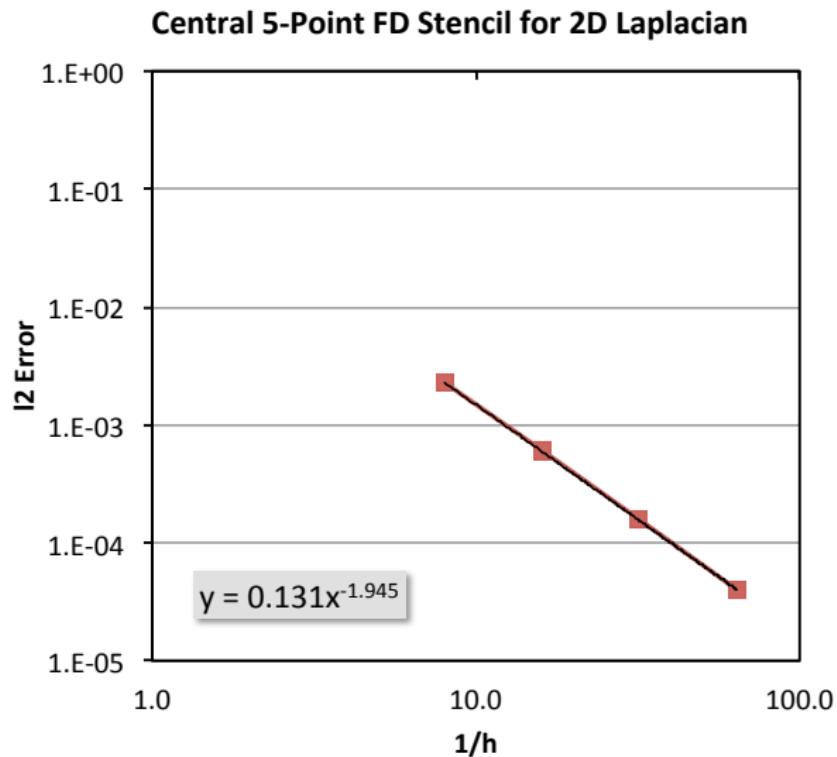
## Outline

- Write a program in C/C++, F90, Python, etc.
- *Inputs:*
  - ▶ # of points in one direction ( $npts$ )
  - ▶ the physical dimension of one side ( $L_x, L_y$ )
- *Output:*  $l_2$  error between your numerical solution and an exact solution derived from a manufactured solution

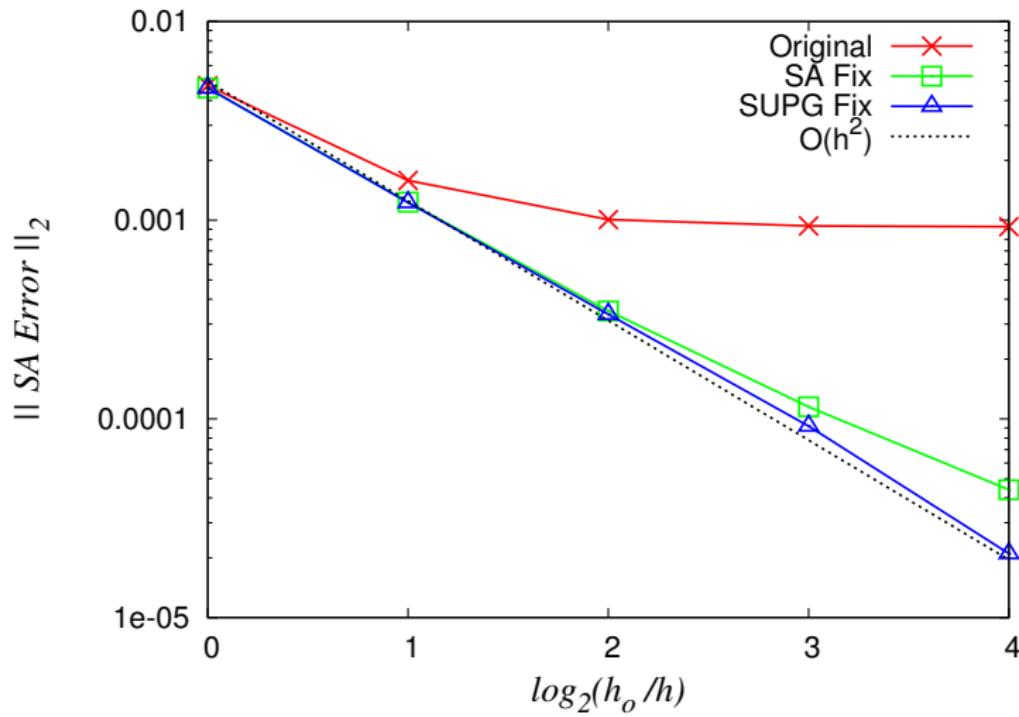
$$l_2 = \sqrt{\frac{\sum_{i=1}^N (\phi_i - \phi_i^{\text{exact}})^2}{N}}$$

- *Runs:* Run your snazzy code for  $npts = 5, 9, 17$ , and  $33$  and plot  $l_2$  norm as a function of  $1/h$  where  $h = \text{length}/(npts - 1)$

## Example Results: What we're hoping for 2nd Order Central Finite-difference Scheme



# This Process Finds Bugs



# Useful for Detecting Subtle Bugs

## Verification of FIN-S

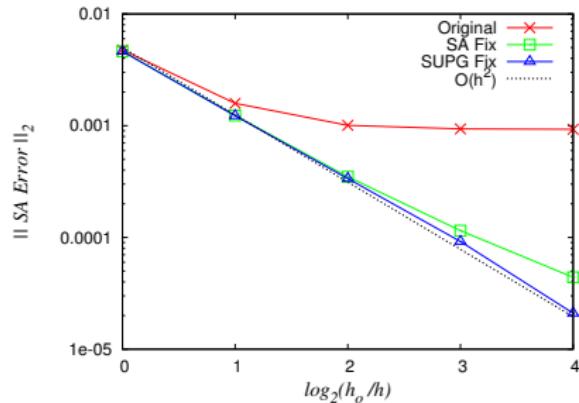
- FANS, Spalart-Allmaras

- Derivative:

$$\frac{d(sa)}{dx} = \frac{1}{\rho} * \left( \frac{d(\rho * sa)}{dx} - sa \frac{d\rho}{dx} \right)$$

- In code:

$$\frac{d(sa)}{dx} = \frac{1}{\rho} * \frac{d(\rho * sa)}{dx} - sa \frac{d\rho}{dx}$$



# Summary

## What we have learned:

- We can generate MS even for systems we do not have solutions for
- The MMS is a powerful method to verify rates of convergence

## Why is this not more commonly done?

- Solution Generation is complex and time intensive
- Meaningful Solution generation can be subtle

# A Real Example

## MMS Creation Process

- Start by “manufacturing” a suitable closed-form exact solution
- For example, the 10 parameter trigonometric solution of the form:  
(Roy, 2002)

$$\hat{u}(x, y, z, t) = \hat{u}_0 + \hat{u}_x f_s\left(\frac{a_{\hat{u}x}\pi x}{L}\right) + \hat{u}_y f_s\left(\frac{a_{\hat{u}y}\pi y}{L}\right) + \\ + \hat{u}_z f_s\left(\frac{a_{\hat{u}z}\pi z}{L}\right) + \hat{u}_t f_s\left(\frac{a_{\hat{u}t}\pi t}{L}\right)$$

- Apply this solution to equations of interest, solve for source terms (residual)

Accomplished using packages such as Maple, Mathematica, SymPy, Macsyma, etc.

# Maple MMS: 3D Navier-Stokes Energy Term

$$\begin{aligned}
Qe = & - \frac{a_{px}\pi p_x}{L} \frac{\gamma}{\gamma - 1} \sin\left(\frac{a_{px}\pi x}{L}\right) \left[ u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right] + \\
& + \frac{a_{py}\pi p_y}{L} \frac{\gamma}{\gamma - 1} \cos\left(\frac{a_{py}\pi y}{L}\right) \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right] + \\
& - \frac{a_{pz}\pi p_z}{L} \frac{\gamma}{\gamma - 1} \sin\left(\frac{a_{pz}\pi z}{L}\right) \left[ w_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right] + \\
& + \frac{a_{px}\pi p_x}{2L} \cos\left(\frac{a_{px}\pi x}{L}\right) \left[ u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right] \left[ \left( u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right)^2 + \right. \\
& \quad \left. + \left[ w_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right]^2 + \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right]^2 \right] + \\
& - \frac{a_{py}\pi p_y}{2L} \sin\left(\frac{a_{py}\pi y}{L}\right) \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right] \left[ \left( u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right)^2 + \right. \\
& \quad \left. + \left[ w_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right]^2 + \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right]^2 \right] + \\
& + \frac{a_{pz}\pi p_z}{2L} \cos\left(\frac{a_{pz}\pi z}{L}\right) \left[ w_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right] \left[ \left( u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right)^2 + \right. \\
& \quad \left. + \left[ w_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right]^2 + \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right]^2 \right] + \\
& + \frac{a_{ux}\pi u_x}{2L} \cos\left(\frac{a_{ux}\pi x}{L}\right) \left( \left[ \left( u_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right)^2 + \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right]^2 \right. \right. + \\
& \quad \left. \left. + 3 \left[ u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right]^2 \right] \left[ \rho_0 + \rho_x \sin\left(\frac{a_{px}\pi x}{L}\right) + \rho_y \cos\left(\frac{a_{py}\pi y}{L}\right) + \rho_z \sin\left(\frac{a_{pz}\pi z}{L}\right) \right] + \right. \\
& \quad \left. + \left[ p_0 + p_x \cos\left(\frac{a_{px}\pi x}{L}\right) + p_y \sin\left(\frac{a_{py}\pi y}{L}\right) + p_z \cos\left(\frac{a_{pz}\pi z}{L}\right) \right] \frac{2\gamma}{(\gamma - 1)} \right) + \\
& - \frac{a_{uy}\pi u_y}{L} \sin\left(\frac{a_{uy}\pi y}{L}\right) \left[ v_0 + v_x \cos\left(\frac{a_{vx}\pi x}{L}\right) + v_y \sin\left(\frac{a_{vy}\pi y}{L}\right) + v_z \sin\left(\frac{a_{vz}\pi z}{L}\right) \right] \left[ \rho_0 + \rho_x \sin\left(\frac{a_{px}\pi x}{L}\right) + \rho_y \cos\left(\frac{a_{py}\pi y}{L}\right) + \rho_z \sin\left(\frac{a_{pz}\pi z}{L}\right) \right] \cdot \\
& \quad \cdot \left[ u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right] + \\
& - \frac{a_{uz}\pi u_z}{L} \sin\left(\frac{a_{uz}\pi z}{L}\right) \left[ w_0 + w_x \sin\left(\frac{a_{wx}\pi x}{L}\right) + w_y \sin\left(\frac{a_{wy}\pi y}{L}\right) + w_z \cos\left(\frac{a_{wz}\pi z}{L}\right) \right] \left[ \rho_0 + \rho_x \sin\left(\frac{a_{px}\pi x}{L}\right) + \rho_y \cos\left(\frac{a_{py}\pi y}{L}\right) + \rho_z \sin\left(\frac{a_{pz}\pi z}{L}\right) \right] \cdot \\
& \quad \cdot \left[ u_0 + u_x \sin\left(\frac{a_{ux}\pi x}{L}\right) + u_y \cos\left(\frac{a_{uy}\pi y}{L}\right) + u_z \cos\left(\frac{a_{uz}\pi z}{L}\right) \right] +
\end{aligned}$$

## But wait, there's more!

## C-code output

# Meaningful Verification is difficult

## What Constitutes a Robust Test?

- How “strong” is a verification test for a particular codebase?
  - ▶ Can you characterize your confidence in a codebase?
  - ▶ What constitutes a strong test?

## Verification Metrics

- In general, you cannot “verify” a codebase
  - ▶ You can, however, detect **verification failures**

## Physically-based MS

- Exercise each term in the PDE in a similar way to that of a real solution

# Example Problem

## Complex Codebase

- Finite Element hypersonic code, fully implicit Navier-Stokes (FIN-S)
- Favre-Averaged Navier Stokes (FANS) + Spalart-Allmaras (SA) turbulence model

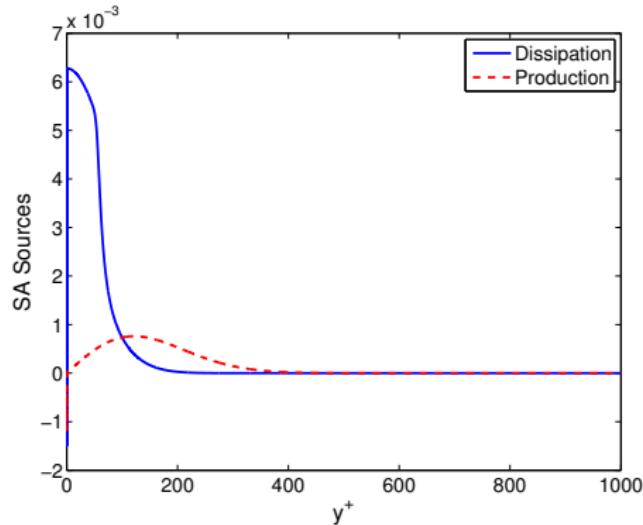
## FANS + SA

$$\begin{aligned} \frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{\rho} \tilde{u}_i) &= 0 \\ \frac{\partial}{\partial t} (\bar{\rho} \tilde{u}_i) + \frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_j \tilde{u}_i) &= - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( 2(\mu + \mu_t) \tilde{S}_{ji} \right) \\ \frac{\partial}{\partial t} \left[ \bar{\rho} \left( \tilde{e} + \frac{1}{2} \tilde{u}_i \tilde{u}_i \right) \right] + \frac{\partial}{\partial x_j} \left[ \bar{\rho} \tilde{u}_j \left( \tilde{h} + \frac{1}{2} \tilde{u}_i \tilde{u}_i \right) \right] &= \frac{\partial}{\partial x_j} \left( 2(\mu + \mu_t) \tilde{S}_{ji} \tilde{u}_i \right) + \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{Pr} + \frac{\mu_t}{Pr_t} \right) \frac{\partial \tilde{h}}{\partial x_j} \right] \\ \frac{\partial}{\partial t} (\bar{\rho} \nu_{sa}) + \frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_j \nu_{sa}) &= c_{b1} S_{sa} \bar{\rho} \nu_{sa} - c_{w1} f_w \bar{\rho} \left( \frac{\nu_{sa}}{d} \right)^2 + \frac{1}{\sigma} \frac{\partial}{\partial x_k} \left[ (\mu + \bar{\rho} \nu_{sa}) \frac{\partial \nu_{sa}}{\partial x_k} \right] + \frac{c_{b2}}{\sigma} \bar{\rho} \frac{\partial \nu_{sa}}{\partial x_k} \frac{\partial \nu_{sa}}{\partial x_k} \end{aligned}$$

# Insufficient Verification

## Shortcoming of other SA MS

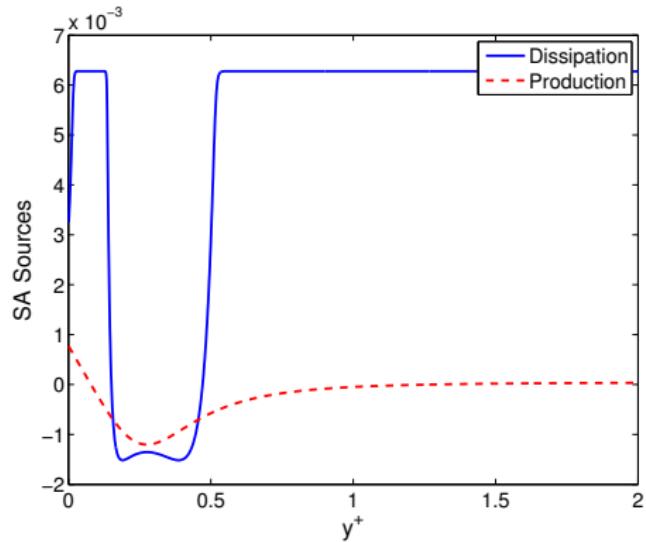
- Bond solution: sinusoidal, only satisfies no-slip.
- Eça solutions: noted to have a suboptimal rate of convergence



# A Closer Look

## Shortcoming of other SA MS

- Eça solutions are shown to have instabilities or near-wall features that disrupt the correct rate of convergence
  - Offending term:  $\nu_{sa} = \tilde{\nu}_{\max} \eta_{\nu}^2 e^{1-\eta_{\nu}^2}$



# Our SA Manufactured Solution

- Use our understanding of incompressible flow physics to inform our modeling assumptions for this MS

## Streamwise Velocity

- The mean streamwise velocity is given by,

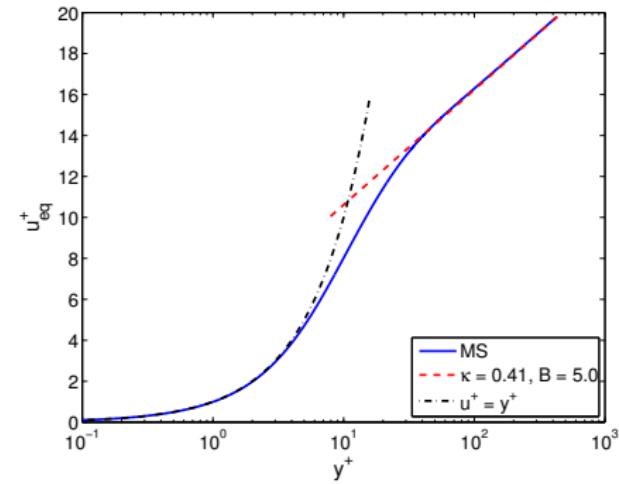
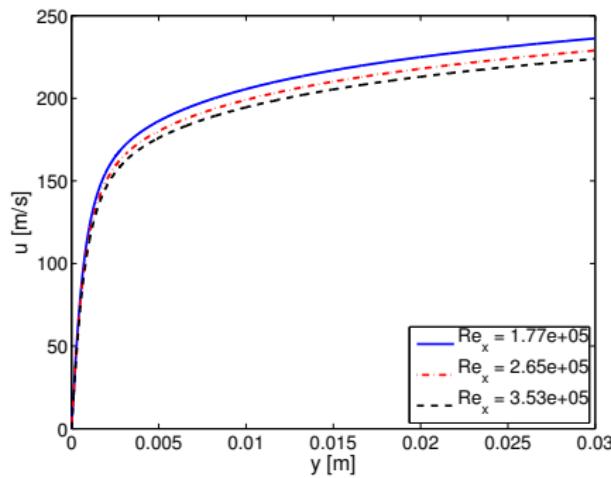
$$\tilde{u} = \frac{u_\infty}{A} \sin \left( \frac{A}{u_\infty} u_{eq} \right)$$

The van Driest equivalent velocity can be written as,

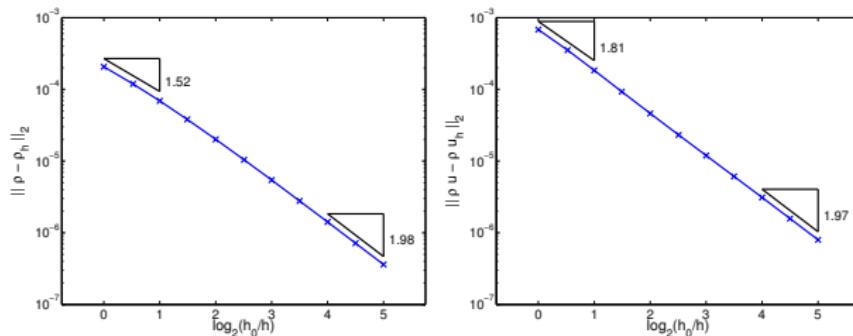
$$u_{eq} = u_\tau u_{eq}^+,$$

- Must specify both  $u_\tau$  and  $u_{eq}^+$

# Manufactured Velocity Profiles

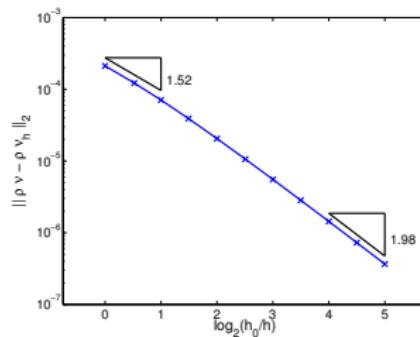


# Convergence Rates: $Re_x$



(a)  $\bar{\rho}$

(b)  $\bar{\rho}\tilde{u}$



(c)  $\bar{\rho}\nu_{sa}$

# Summary

## What we have learned:

- Be skeptical of an MS like you would be skeptical of a model
  - ▶ Manufactured Solutions must be verified!
- Exercise each term in the PDE in a similar way to that of a real solution
- *More details:* “Manufactured Solutions for the Favre-Averaged Navier-Stokes Equations with Eddy-Viscosity Turbulence Models”
  - ▶ AIAA 50th Aerospace Sciences Meeting

## Why is this not more commonly done?

- Manufactured Solution generation is a time consuming process
  - ▶ Rule of 10%
- Domain expert input needed to generate manufactured solutions!

# Manufactured Analytical Solutions Abstractions Library

**Goal:** Provide a repository and standardized interface for MMS usage

## High Priority:

- Extreme fidelity to generated MMS
- Portability
- Traceability
- Extensible

## Low Priority:

- Speed/Performance

# Verifying the “Verifier”

Precision is not negotiable.

## MASA Testing

- Error target < 1e-15
  - ▶ Absolute error on local machines
  - ▶ Relative error (other)
  - ▶ On all supported compiler sets
- -O0 not sufficient
  - ▶ -fp-model precise (Intel)
  - ▶ -fno-unsafe-math-optimizations (GNU)
  - ▶ -Kieee -Mnofpapprox (PGI)
- “make check”
  - ▶ Run by Buildbot every two hours

```
[nick@magus trunk]$ make check
```

```
-----
```

```
Initializing MASA Tests
```

```
-----
```

```
PASS: init.sh
PASS: misc
PASS: fail_cond
PASS: catch_exception
PASS: register
PASS: poly
PASS: uninit
PASS: vec
PASS: purge
PASS: heat_const_steady
PASS: euler1d
```

```
: : :
```

```
-----
```

```
Finalizing MASA Tests
```

```
-----
```

```
=====
```

```
All 65 tests passed
```

```
=====
```

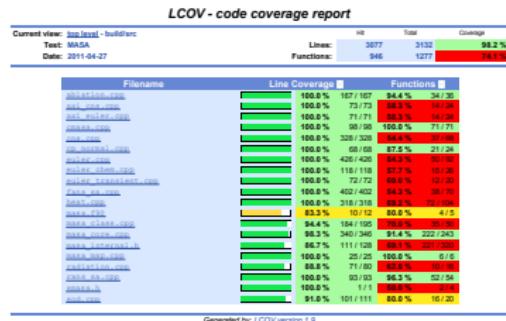
# Portability

## Software Environment

- Built with: Autotools, C++
- Supports Intel, GNU, Portland Group compilers
- C/C++ interfaces
- Fortran interfaces provided through **iso\_c\_bindings**
  - ▶ Fortran 2003 Standard
- Python interfaces generated with **SWIG**

## Testing

- GIT: version control
- Buildbot: automated testing
- GCOV: line coverage
  - ▶ 15,826 lines of code
  - ▶ 13,195 lines of testing
  - ▶ 98%+ line coverage



# Traceability

## Doxygen provides code and model documentation

### 3.2 Euler Equations

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where  $\phi = \rho, u, v, w$  or  $p$ , and  $f_a(\cdot)$  functions denote either sine or cosine function. Note that in this case,  $\phi_x, \phi_y$  and  $\phi_z$  are constants and the subscripts do not denote differentiation.

Although ? provide the constants used in the manufactured solutions for the 2D supersonic and subsonic cases for Euler and Navier-Stokes equations, only the source term for the 2D mass conservation equation (3.20) is presented.

Source terms for mass conservation ( $Q_\rho$ ), momentum ( $Q_u, Q_v$  and  $Q_w$ ) and total energy ( $Q_e$ ) equations are obtained by symbolic manipulations of compressible steady Euler equations above using Maple 13 (?) and are presented in the following sections for the one, two and three-dimensional cases.

#### 3.2.2.1 1D Steady Euler

The manufactured analytical solutions (3.52) for each one of the variables in one-dimensional case of Euler equations are:

$$\begin{aligned} \rho(x) &= \rho_0 + \rho_s \sin\left(\frac{a_{xz}\pi x}{L}\right) \\ u(x) &= u_0 + u_s \sin\left(\frac{a_{xz}\pi x}{L}\right) \\ p(x) &= p_0 + p_s \cos\left(\frac{a_{xz}\pi x}{L}\right) \end{aligned} \quad (3.26)$$

The MMS applied to Euler equations consists in modifying the 1D Euler equations (3.20) – (3.22) by adding a source term to the right-hand side of each equation:

$$\begin{aligned} \frac{\partial(\rho u)}{\partial x} &= Q_\rho \\ \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(p)}{\partial x} &= Q_u \\ \frac{\partial(\rho u v_t)}{\partial x} + \frac{\partial(\rho u)}{\partial x} &= Q_v \\ \end{aligned} \quad (3.27)$$

so the modified set of equations (3.27) conveniently has the analytical solution given in Equation (3.53).

Source terms  $Q_\rho, Q_u$  and  $Q_v$  are obtained by symbolic manipulations of equations above using Maple and are presented in the following sections. The following auxiliary variables have been included in order to improve readability and computational efficiency:

$$\begin{aligned} \text{Rho}_1 &= \rho_0 + \rho_s \sin\left(\frac{a_{xz}\pi x}{L}\right) \\ U_1 &= u_0 + u_s \sin\left(\frac{a_{xz}\pi x}{L}\right) \\ P_1 &= p_0 + p_s \cos\left(\frac{a_{xz}\pi x}{L}\right) \end{aligned}$$

where the subscripts refer to the 1D case.

The mass conservation equation written as an operator is:

$$\mathcal{L} = \frac{\partial(\rho u)}{\partial x}$$

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### 3.2 Euler Equations

29

$k$	$u\_0$	$u\_x$	$u\_y$	$u\_z$	$v\_0$	$v\_x$	$v\_y$	$v\_z$	$w\_0$	$w\_x$	$w\_y$	$w\_z$
$v\_0$	$v\_x$	$v\_y$	$v\_z$		$w\_0$	$w\_x$	$w\_y$	$w\_z$				
$\rho u_0$	$\rho u_x$	$\rho u_y$	$\rho u_z$		$\rho v_0$	$\rho v_x$	$\rho v_y$	$\rho v_z$	$\rho w_0$	$\rho w_x$	$\rho w_y$	$\rho w_z$
$\rho u_x$	$\rho u_{xx}$	$\rho u_{xy}$	$\rho u_{xz}$		$\rho v_x$	$\rho v_{xx}$	$\rho v_{xy}$	$\rho v_{xz}$	$\rho w_x$	$\rho w_{xx}$	$\rho w_{xy}$	$\rho w_{xz}$
$\rho u_y$	$\rho u_{yx}$	$\rho u_{yy}$	$\rho u_{yz}$		$\rho v_y$	$\rho v_{yx}$	$\rho v_{yy}$	$\rho v_{yz}$	$\rho w_y$	$\rho w_{yx}$	$\rho w_{yy}$	$\rho w_{yz}$
$\rho u_z$	$\rho u_{zx}$	$\rho u_{zy}$	$\rho u_{zz}$		$\rho v_z$	$\rho v_{zx}$	$\rho v_{zy}$	$\rho v_{zz}$	$\rho w_z$	$\rho w_{zx}$	$\rho w_{zy}$	$\rho w_{zz}$
$\mu$	$\Gamma$											

Table 3.6: Parameters used by the 3D Steady Euler

- `masa_eval_2d_exact_u()`
- `masa_eval_2d_exact_v()`
- `masa_eval_2d_exact_p()`
- `masa_eval_2d_exact_rho()`
- `masa_eval_2d_grad_u()`
- `masa_eval_2d_grad_v()`
- `masa_eval_2d_grad_p()`
- `masa_eval_2d_grad_rho()`

#### 3.2.3.3 3D Steady Euler

Initialization:

- `euler_3d`

Functions:

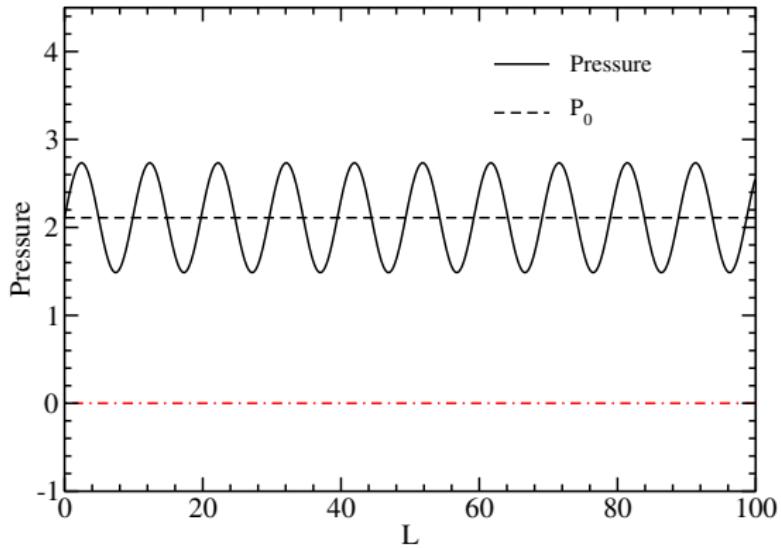
- `masa_init()`
- `masa_eval_3d_source_rho_u()`
- `masa_eval_3d_source_rho_v()`
- `masa_eval_3d_source_rho_w()`
- `masa_eval_3d_source_rho_e()`
- `masa_eval_3d_source_rho_t()`
- `masa_eval_3d_exact_u()`
- `masa_eval_3d_exact_v()`
- `masa_eval_3d_exact_w()`
- `masa_eval_3d_exact_p()`

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# Providing Reasonable Defaults

## Requirements:

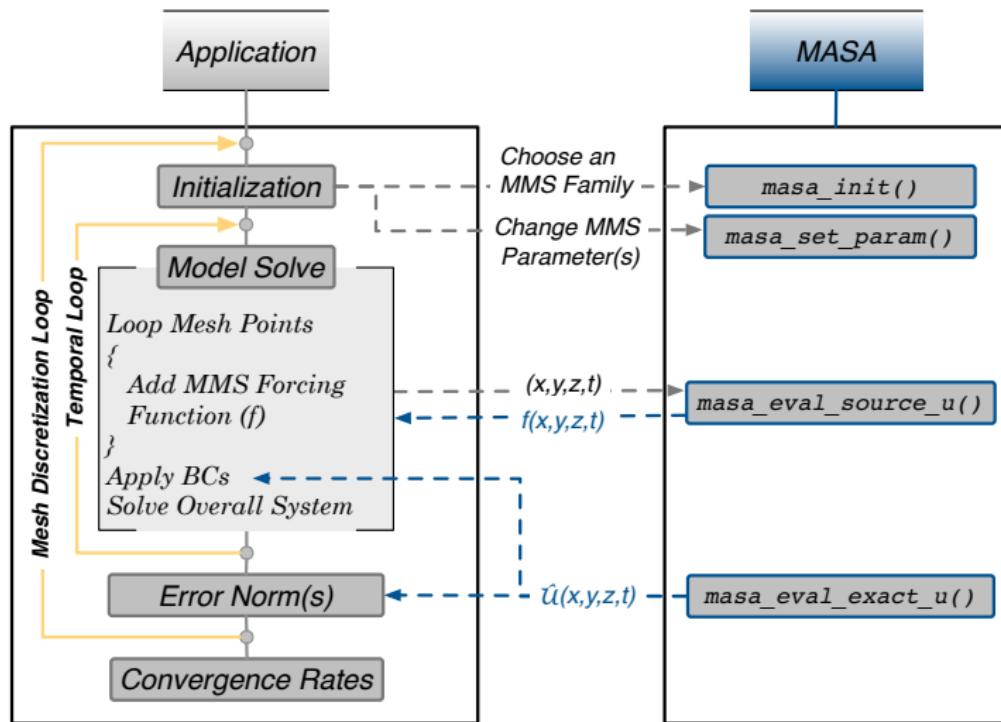
- Sufficient algebraic complexity to exercise all terms
- Physically consistent
  - ▶ e.g. solutions should not return negative densities, temperatures, etc.



# Available Solutions in MASA 0.44.0

Equations	Dimensions	Time
Euler	1,2,3, axi	Transient, Steady
Non linear heat conduction	1,2,3	Transient, Steady
Navier-Stokes	1,2,3, axi	Transient, Steady
N-S + Sutherland	3	Transient, Steady
N-S + ablation	1	Transient, Steady
Burgers	2	Transient, Steady
Sod Shock Tube	1	Transient
Euler + chemistry	1	Steady
RANS: Spalart-Allmaras	1	Steady
FANS: SA	2	Steady
FANS: SA + wall	2	Steady
Radiation	1	Steady
SMASA: Gaussian	1	Steady

# General Verification Approach Using MMS and MASA



# Fortran 90: What you need from MASA

```
program main
  use masa
  implicit none

  dx = real(lx)/real(nx)
  dy = real(ly)/real(ny);

  ! initialize the problem
  call masa_init("laplace example","laplace_2d")

  ! evaluate source terms (2D)
  do i=0, nx
    do j=0, ny

      y = j*dy
      x = i*dx

      ! evaluate source term
      field = masa_eval_2d_source_f (x,y)

      ! evaluate analytical term
      exact_phi = masa_eval_2d_exact_phi (x,y)

    enddo
  enddo

end program main
```

## C: What you need from MASA

```
#include <masa.h>

int main()
{
    err += masa_init("laplace example","laplace_2d");

    // grab / set parameter values
    Lx = masa_get_param("Lx");
    masa_set_param("Ly",42.0);

    for(int i=0;i<nx;i++)
        for(int j=0;j<nx;j++)
    {
        x=i*dx;
        y=j*dy;

        // source term
        ffield = masa_eval_2d_source_f (x,y);

        // manufactured solution
        phi_field = masa_eval_2d_exact_phi(x,y);

    } // finished iterating over space
} //end program
```

# Python: What you need from MASA

```
#  
# import .libs relative path for masa.py  
#  
import os, sys  
import numpy as np  
lib_path = os.path.abspath('../src/.libs')  
sys.path.append(lib_path)  
import _masa  
  
err = 0  
err += _masa.masa_init("laplace example","laplace_2d")  
  
space = np.linspace(0,1.0,num=5)  
for x in np.nditer(space):  
    for y in np.nditer(space):  
        ffield = _masa.masa_eval_2d_source_f(x,y)  
        phi_field = _masa.masa_eval_2d_exact_phi(x,y)  
  
if(err == 0):  
    # Steady as she goes  
    sys.exit(0)  
else:  
    # something is wrong  
    sys.exit(1)
```

# Future Solution Development

## Single Physics

- Additional RANS models ( $v^2$ -f, k- $\epsilon$ , etc.)
- Shocks

## Stochastic PDEs

- Conjugate Priors
- Fokker-Plank (time evolution of pdfs)
- How do you verify something that is random?

## Different physical systems

- Einstein's field equations (General Relativity)
- Schrodinger equation (Quantum Mechanics)
- Black-Scholes (Finance)
- etc.

# Importing New Solutions

## Requirements

- Latex documents can be loaded directly into MASA documentation
  - ▶ Model document detailing analytical solution and source terms
  - ▶ Interface documentation detailing parameters and functions
- Source and analytical terms in C/C++/Fortran90
  - ▶ Can be integrated into your local MASA copy automagically (perl!)
  - ▶ Submit a patch
    - (unit tests would be nice)
- Willingness to share
- Publish these solutions!
- Success of MASA depends on use as a community tool

# Shortcomings

## Symbolic Shortcomings

- Even with factorization, source terms still massive
- Generating manufactured solutions was a **full time job** at PECOS
- Everything we have discussed has been generated outside of MASA
  - ▶ Not thrilled with Maple, Mathematica

## Enter Automatic Differentiation

- AD numerically evaluates the derivative of a function
  - ▶ applies chain rule repeatedly
- Superior error characteristics (round-off)
- Slow (but we barely care)
- Several libraries: NAG, Sacado, etc.

# MASA PDE Examples

## Source Terms: Euler

```
// Arbitrary manufactured solutions
U.template get<0>() = u_0 + u_x * sin(a_ux * PI * x / L)
                      + u_y * cos(a_uy * PI * y / L);
```

$$\nabla \cdot (\rho u) = 0$$

$$\nabla \cdot (eu) + p \nabla \cdot u = 0$$

```
// Mass, momentum and energy
Scalar Q_rho    = raw_value(divergence(RHO*U));
RawArray Q_rho_u = raw_value(divergence(RHO*U.outerproduct(U)) +
                           P.derivatives());
Scalar Q_rho_e = raw_value(divergence((RHO*ET+P)*U));
```

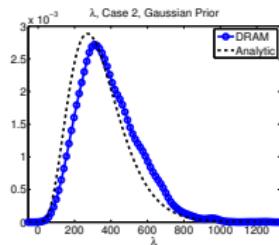
# SMASA: Stochastic MASA

## State-of-the-Art

- Verification of Bayesian model calibration algorithms
- Uses non-deterministic linear regression model:

$$y = G\beta + \epsilon(\lambda, \phi)$$

- $y$  observations,  $G$  response matrix,  $\beta$  unknowns,  $\epsilon$  noise
- Must define energy norm to estimate convergence
- Two forms of priors: non-informative (Jeffreys) and Gaussian



# Snapshot

## Release

- MASA 0.44.0 current release – 0.50 COMING SOON
- <https://github.com/manufactured-solutions/MASA>
- Open source, LGPL V2.1, free

## Publications

- “MASA: a library for verification using manufactured analytical solutions”
  - ▶ DOI: 10.1007/s00366-012-0267-9
- A TRANSIENT MANUFACTURED SOLUTION FOR THE COMPRESSIBLE NAVIER-STOKES EQUATIONS WITH A POWER LAW VISCOSITY
- Manufactured Solutions for the Favre-Averaged Navier-Stokes Equations with Eddy-Viscosity Turbulence Models
- “A Linear Regression Framework for the Verification of Bayesian Model Calibration Algorithms” (submitted to ASME VVUQ)

# Conclusions

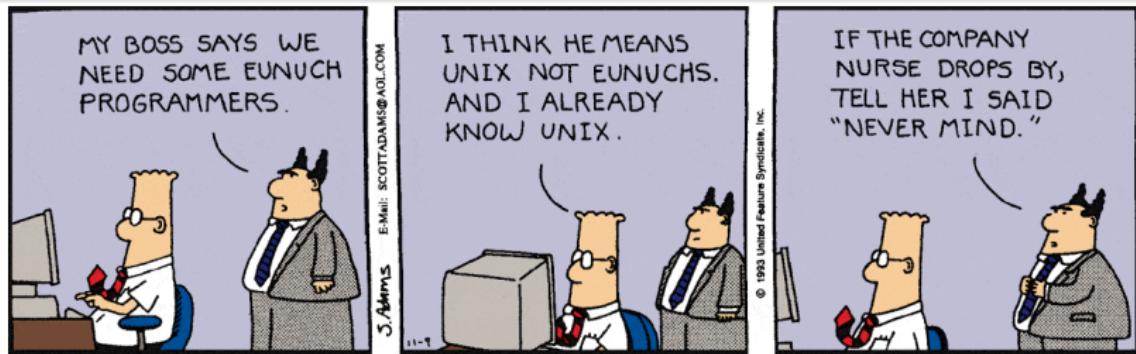
## Summary

- MMS is not a difficult concept, but can be tricky and time consuming
- Must have a high degree of confidence in your verification suite
- MASA is an open source library designed to:
  - ▶ Increase use of existing MMS in the community
  - ▶ Provide a standardized interface and toolset to the community
  - ▶ Serve as an example of high quality verification software

# Conclusions

Have a well verified day.

nicholas.malaya@gmail.com



# Combinatorial Explosion

## Explosion in source term size

- Complexity increases with more sophisticated mathematical models
  - ▶ Sutherland viscosity model has over 1,612,000 characters
- Large memory requirements (128 GB not sufficient for Sutherland)
- Computational intensity
- **segfaults**

## Hierarchic MMS

- Decompose each equation into sub-terms
- Each term is operated on individually to plug in a manufactured solution
- Resulting expressions are re-combined to regain source term

# The Hierarchic MMS

Consider the full 3D Navier-Stokes energy equation:

$$\mathcal{L} = \frac{\partial(\rho e_t)}{\partial t} + \nabla \cdot (\rho \mathbf{u} e_t) + \nabla \cdot \mathbf{q} + \nabla \cdot (p \mathbf{u}) - \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u})$$

Decompose:

$$\mathcal{L}_1 = \frac{\partial(\rho e_t)}{\partial t}$$

$$\mathcal{L}_2 = \nabla \cdot (\rho \mathbf{u} e_t)$$

$$\mathcal{L}_3 = \nabla \cdot \mathbf{q}$$

$$\mathcal{L}_4 = \nabla \cdot (p \mathbf{u})$$

$$\mathcal{L}_5 = -\nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u})$$

Hierarchic MMS extensions:

- Expand each component of divergence
- Transient and steady cases ( $\mathcal{L}_1 = 0$ )
- Sutherland model only requires altering  $\mathcal{L}_5$
- Navier-Stokes  $\rightarrow$  Euler and additional terms

# Hierarchic MMS Results

## Reductions

- Symbolic factorization tricks permit further simplification of these operators:

Term	Before	After	Reduction
$\mathcal{L}_1$	$70.1 \times 10^3$	$1.1 \times 10^3$	98.4%
$\mathcal{L}_2$	$292.8 \times 10^3$	$4.0 \times 10^3$	98.6%
$\mathcal{L}_3$	$11.3 \times 10^3$	$1.2 \times 10^3$	89.3%
$\mathcal{L}_4$	$1.5 \times 10^3$	$5.8 \times 10^2$	61.3%
$\mathcal{L}_5$	$3.1 \times 10^3$	$1.3 \times 10^3$	58.0%
$\mathcal{L}$	$378.8 \times 10^3$	$8.2 \times 10^3$	97.8%

## Reduced source term C-output

# Original source term C-output

# Shortcomings

## Symbolic Shortcomings

- Hierarchic decomposition is an improvement, but is it enough?
  - ▶ Even with factorization, source terms still massive
  - ▶ Generating manufactured solutions was a **full time job** at PECOS
- Everything we have discussed has been generated outside of MASA
  - ▶ Not thrilled with Maple, Mathematica

## Enter Automatic Differentiation

- AD numerically evaluates the derivative of a function
  - ▶ applies chain rule repeatedly
- Superior error characteristics (round-off)
- Slow (but we barely care)
- Several libraries: NAG, Sacado, etc.

# Review: Complex Numbers

- A new element  $i$
- Take the quotient with  $i^2 \equiv -1$

$$\mathbb{C}[\mathbb{R}] \equiv \{a + bi : a, b \in \mathbb{R}\}$$

- Arithmetic:

$$(a + bi) + (c + di) = ((a + c) + (b + d)i)$$

$$(a + bi) - (c + di) = ((a + c) - (b + d)i)$$

$$\begin{aligned}(a + bi) \times (c + di) &= (ac) + adi + bci + bdi^2 \\&= ((ac) + (ad + bc)i - (bd))\end{aligned}$$

## “Dual Numbers” - [Clifford 1873],[Study 1891]

- A new element  $\epsilon$
- Closed under addition and multiplication:

$$\left\{ \sum_{i=0}^m a_i \epsilon^i : a_i \in \mathbb{R}, m < \infty \right\}$$

- Take the quotient with  $\epsilon^2 \equiv 0$

$$\mathbb{D}[\mathbb{R}] \equiv \{a + b\epsilon : a, b \in \mathbb{R}\}$$

- Used with quaternions to represent rotations and translations
- Arithmetic:

$$(a + b\epsilon) + (c + d\epsilon) = ((a + c) + (b + d)\epsilon)$$

$$(a + b\epsilon) - (c + d\epsilon) = ((a + c) - (b + d)\epsilon)$$

$$\begin{aligned}(a + b\epsilon) \times (c + d\epsilon) &= (ac) + ade + bc\epsilon + bd\epsilon^2 \\&= ((ac) + (ad + bc)\epsilon)\end{aligned}$$

## “Hyper-dual Numbers” - [Fike 2009]

- Add two new elements  $\epsilon_1, \epsilon_2$  to  $\mathbb{R}$
- Take the quotient with  $\epsilon_1^2 \equiv \epsilon_2^2 \equiv 0$

$$\mathbb{H}[\mathbb{R}] \equiv \{a + b\epsilon_1 + c\epsilon_2 + d\epsilon_1\epsilon_2 : a, b, c, d \in \mathbb{R}\}$$

- Arithmetic:

$$(a + b\epsilon_1 + c\epsilon_2 + d\epsilon_1\epsilon_2) + (e + f\epsilon_1 + g\epsilon_2 + h\epsilon_1\epsilon_2) =$$

$$((a + e) + (b + f)\epsilon_1 + (c + g)\epsilon_2 + (d + h)\epsilon_1\epsilon_2)$$

$$(a + b\epsilon_1 + c\epsilon_2 + d\epsilon_1\epsilon_2) - (e + f\epsilon_1 + g\epsilon_2 + h\epsilon_1\epsilon_2) =$$

$$((a - e) + (b - f)\epsilon_1 + (c - g)\epsilon_2 + (d - h)\epsilon_1\epsilon_2)$$

$$(a + b\epsilon_1 + c\epsilon_2 + d\epsilon_1\epsilon_2) \times (e + f\epsilon_1 + g\epsilon_2 + h\epsilon_1\epsilon_2) =$$

$$(ae) + (af + be)\epsilon_1 + (ag + ce)\epsilon_2 + (ah + de + bg + cf)\epsilon_1\epsilon_2$$

# “Hyper-Dual Numbers”

- With  $\epsilon_1^2 \equiv \epsilon_2^2 \equiv 0 \equiv (\epsilon_1\epsilon_2)^2 = 0$
- Where  $X \equiv x + \epsilon_1 + \epsilon_2$ , we find:

$$f(X) = f(x) + f'(x)\epsilon_1 + f'(x)\epsilon_2 + f''(x)\epsilon_1\epsilon_2$$

- The Taylor series truncates exactly at the second-derivative term
- Using hyper-dual numbers results in first- and second-derivative calculations that are exact, regardless of step size
- Methods for computing exact higher derivatives can be created by using more non-real parts ( $\epsilon_3$ , for instance)
  - ▶ Accomplished using Templates in C++