An Open-Source Simulation Tool for Study and Design of Spacecraft Attitude Control Systems

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Three Audiences for This Talk?

- The User
  - "How do I solve today's problem, today?"
- The Developer
  - "What does a sim look like on the inside?"
- The Modeler
  - "Okay, fine, but what can it *do*?"

42 from the User's Perspective

The User Experience

- 42 is a command-line program
- Setup performed with plain text input files
  - Simulation parameters and settings
  - Spacecraft, orbit parameters and initial conditions
- Runs with or without graphics
  - Graphics adds situational awareness
  - Sim runs faster without graphics
- Plain-text output files produced for post-run analysis
- Graphics frames may be captured
  - Stitched together into movies using other software (eg. ffmpeg)

Rapid Prototyping

- Some studies may be conducted without any C coding
- Simple attitude command profiles may be specified in Inp_Cmd.txt
- "Prototype" control law follows that profile
- Sufficient for many concept studies
  - Evaluate instrument fields of regard
  - Size wheels, magnetic torquers for environment

Example Inp_Cmd.txt

```
<<<<<<<<<<<<<<<<<<  42:  Command Script File  >>>>>>>>>>>>>>>>>
0.0 SC[0] qrl = [0.0 0.0 0.0 1.0]
0.0 Point SC[1].B[0] Primary Vector [0.0 0.0 -1.0] at SUN
0.0 Align SC[1].B[0] Secondary Vector [0.0 1.0 0.0] with L-frame Vector [0.0 1.0 0.0]
0.0 Point SC[2].B[0] Primary Vector [0.0 0.0 -1.0] at SC[1]
0.0 Align SC[2].B[0] Secondary Vector [0.0 1.0 0.0] with L-frame Vector [0.0 1.0 0.0]
0.0 Align SC[3].B[0] Primary Vector [0.0 0.0 1.0] with L-frame Vector [1.0 0.0 1.0]
0.0 Point SC[3].B[0] Secondary Vector [1.0 0.0 0.0] at SUN
0.0 SC[4] Cmd Angles = [-90.0 -90.0 0.0] Seq = 131 wrt N Frame
```

In-Depth Studies

- More in-depth studies will require C coding
  - Write your own control laws, "flight software"
    - Some examples provided as a jumping-off point
  - Add custom sensor and actuator models
  - Add output to files to support your analysis needs

Matlab + 42 = Monte Carlo

- 42 can be called from within Matlab using the `system` command
- Use Matlab as the MC executive
  - Generate initial conditions, parameters
  - Write to 42's input files
  - Run 42
  - Process and save data
  - Repeat
- Use 42 as the high-speed, high-fidelity component

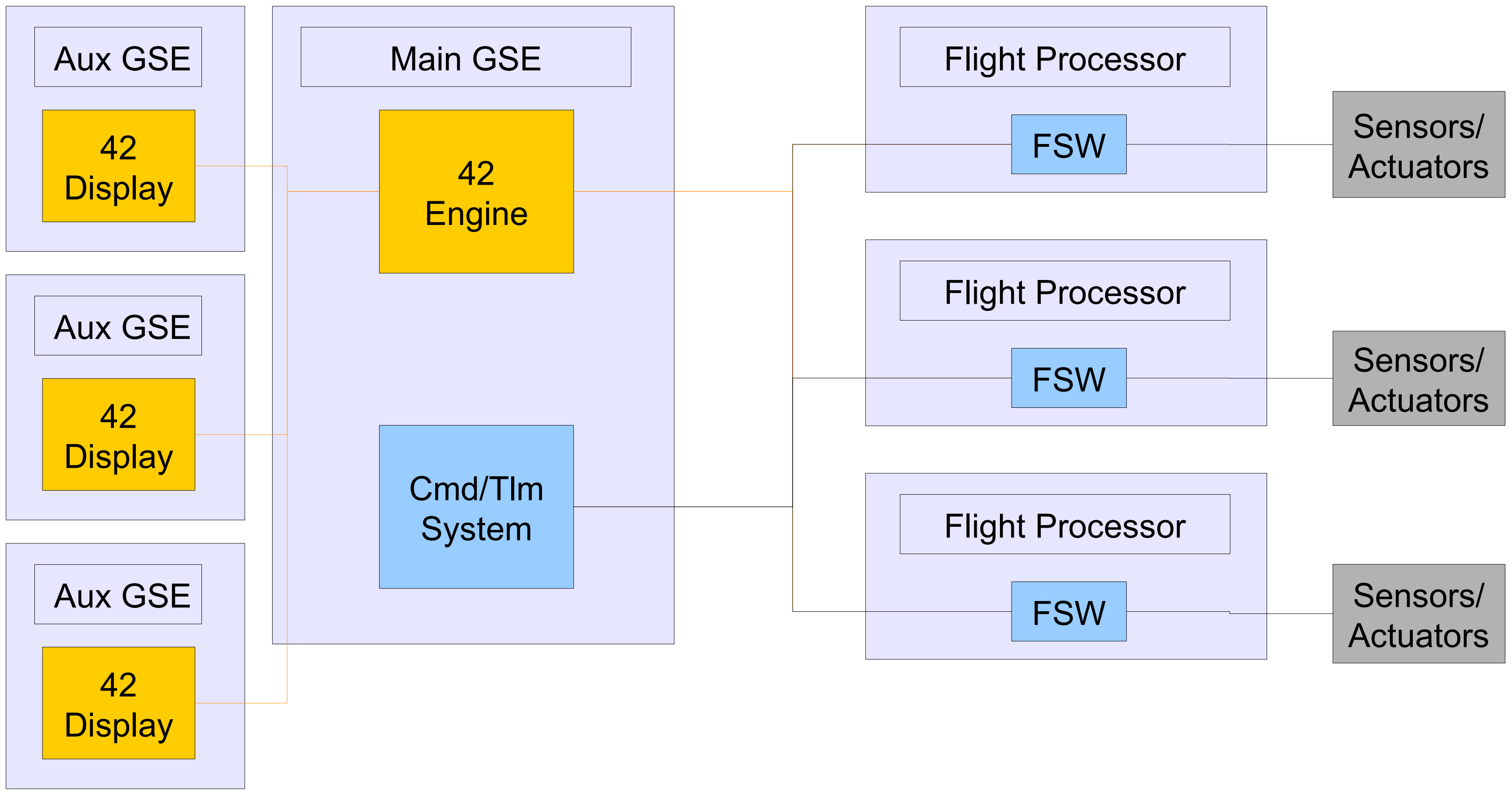
Matlab/42 Example

```
for Irun=1:Nrun,

   % Compute initial attitude
   CRN = TRIAD(tvn(Irun,:),svn,[0 0 1],[1 0 0]);
   qrn = C2Q(CRN);

   % Write target to file
   Outdata = [TrgRA(Irun) TrgDec(Irun)];
   save -ascii ./MOMBIAS/TargetRaDec.inp Outdata

   % Write initial attitude to file
   line = sprintf('%f %f %f %f ! Quaternion\n', qrn(1),qrn(2),qrn(3),qrn(4));
   OverwriteLineInFile('./MOMBIAS/GLAST.inp',21,line);

   % Run 42 for three days.
   system('./42 MOMBIAS');

   % Record pointing histogram.
   load ./MOMBIAS/AngleToGo.42
   [HistCount(Irun,:),HistAng(Irun,:)] = hist(AngleToGo,20);

end
```

Flight Software Testing to Operations

- Eventually, the control laws become flight software, running outside 42 on some other computer
- 42 can communicate over sockets
  - Sim "engine" <-> Flight software
  - Sim "engine" -> Sim "display"
- Splitting engine and display enables multiple displays
- For operations support, displays may be driven by flight telemetry instead of engine

Example: Hardware-in-the-Loop Sim with Multiple Spacecraft



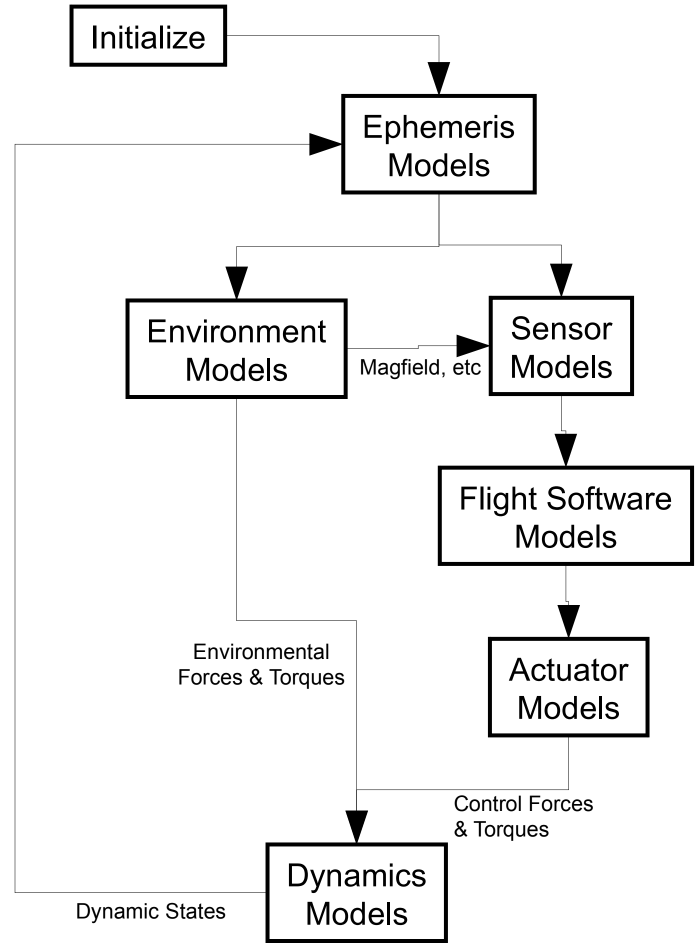
Will It Run On My Computer?

- Most likely
- 42 is open-source, available for download from
  Sourceforge.net/projects/fortytwospacecraftsimulation
- For MacOS and linux, installation is very easy
  - Unzip archive
  - Put 42 folder wherever you want it
  - Edit Makefile to make sure it has your platform correct
  - make and run
- For Windows, there are some external dependencies
  - MinGW, msys provide a linux-style terminal window
  - glew, freeglut required to support graphics
  - Full instructions provided in 42/Docs/Install-msys.txt

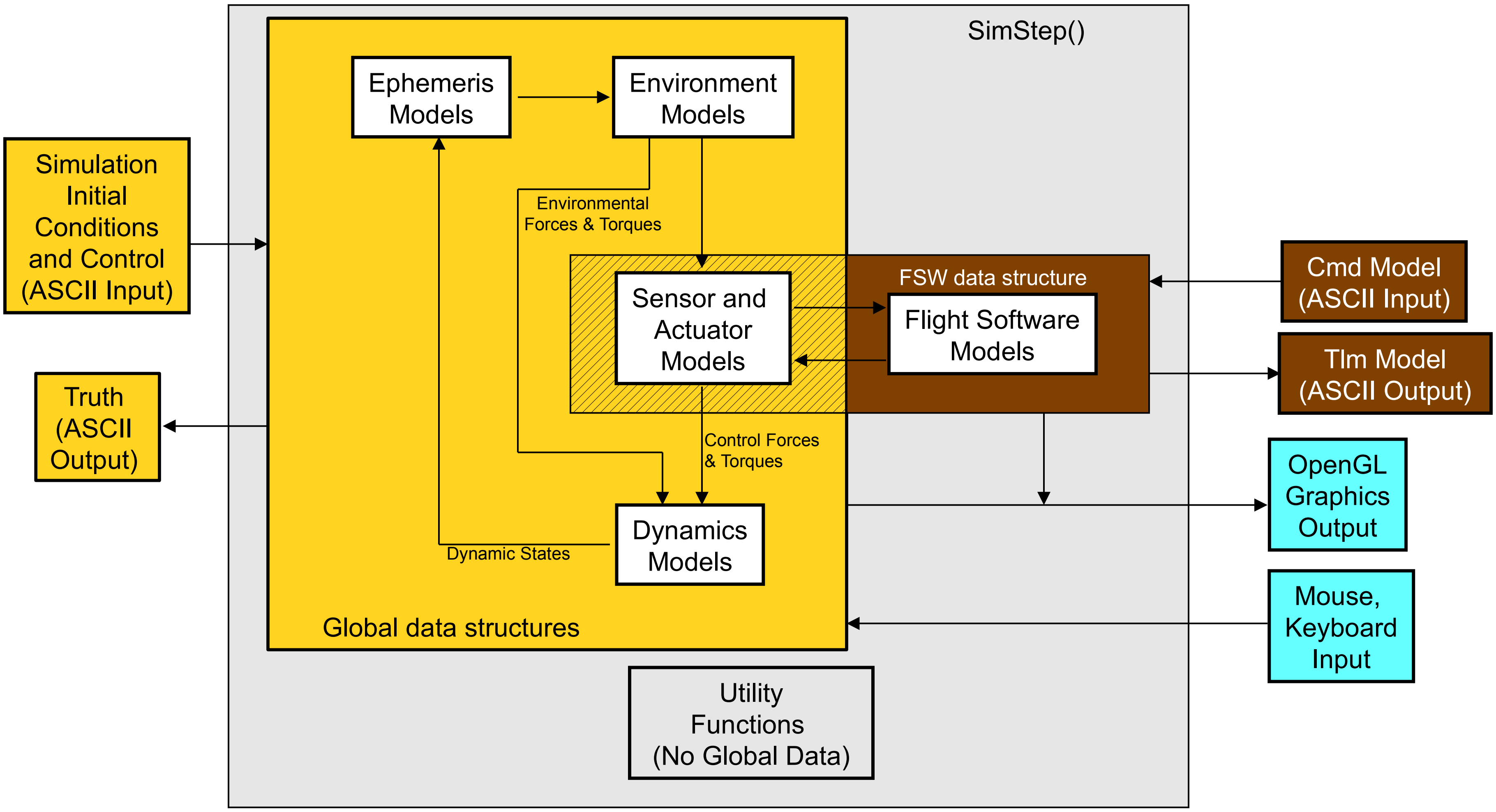
42 from the Developer's Perspective

A Basic Simulation Loop

- Initialize
  - –Read user inputs
  - –Set up
- Ephemeris: Where is everything?
  - –Sun, Earth, Moon, etc
  - –Orbits
  - –Spacecraft
- Environment Models: What forces and torques exerted by the environment?
- Sensor Models
  - –Input truth
  - –Output measurements
- Flight Software Models
  - –Input Measurements
  - –Process Control Laws, etc
  - –Output Actuator Commands
- Actuator Models
  - –Input Commands
  - –Output Forces and Torques
- Dynamics: How does S/C respond to forces and torques?
  - –Integrate dynamic equations of motion over a timestep
  - –Advance time to next step



42's Software Architecture



Good Conventions Make Code Readable, Debuggable

- Choose standard notation to make code readable, unambiguous
  - Think about how notation morphs from the written page to code
- Make code document itself
  - It's much easier to debug

Table 1: Common Reference Frames

N	Inertial Frame (N = Newton)
L	Local Vertical-Local Horizontal
R	Command Frame (R = Reference)
B	Body Frame

Table 2: Commonly-used Expressions

Written	Spoken	Coded
${}^N\vec{\omega}^B$	Angular velocity of B in N	`wbn, SC[i].B[j].wn`
B^*	Mass center of B, "B star"	`SC[i].B[j].cm`
${}^N\vec{v}^{B^*}$	Velocity of B^* in N	`SC[i].B[j].vn`
${}^BC^N$	DCM of B in N (or from N to B)	`CBN, SC[i].B[j].CN`
${}^Bq^N$	Quaternion of B in N (or from N to B)	`qbn, SC[i].B[j].qn`
${}^Av$	Components of v in A, v expressed in A	`va`

Table 3: Common Constructions

Written	Coded
${}^Av = {}^AC^B\,{}^Bv$	`MxV(CAB,vb,va)`
${}^Av = {}^Bv\,{}^BC^A$	`VxM(vb,CBA,va)`
${}^Av = ({}^BC^A)^T\,{}^Bv$	`MTxV(CBA,vb,va)`
${}^Av = {}^Bv({}^AC^B)^T$	`VxMT(vb,CAB,va)`
Convert ${}^BC^N$ to ${}^Bq^N$	`C2Q(CBN,qbn)`
Convert ${}^Bq^N$ to ${}^BC^N$	`Q2C(qbn,CBN)`
Convert Euler Angles (2-1-3 Sequence) to DCM	`A2C(213,ang1,ang2,ang3,C)`
${}^NC^R = ({}^RC^N)^T$	`MT(CRN,CNR)`
${}^BC^R = {}^BC^N({}^RC^N)^T = {}^BC^N\,{}^NC^R$	`MxMT(CBN,CRN,CBR)`
${}^Bq^R = {}^Bq^N \otimes {}^Nq^R$	`QxQT(qbn,qrn,qbr)`

from 42/Docs/Nomenclature.pdf

Reference Frames are Important!

- In any dynamics problem beyond the spinning top, a systematic approach to reference frames and the relationships between them is vital
- For 42, we define several fundamental reference frames, and notational conventions to keep quaternions and direction cosines sorted out

Reference Frames (1 of 2)

- Heliocentric Ecliptic (H)
  - Planet positions expressed in this frame
- Each world has an inertial (N) and rotating (W) frame
  - For Earth, N = ECI (True of date), W = ECEF
  - N is the bedrock for orbits, S/C attitude dynamics
  - Full Disclosure: Although True-of-Date <-> J2000 conversions are provided, the distinction is not always rigorously made
    - Star vectors provided in J2000 (from Skymap), converted to H
    - Planet ephemerides are assumed given in true-of-date H
    - Transformation from N to W is simple rotation, implying N is True-of-Date
    - TOD ↔ J2000 conversions in envkit.c

Reference Frames (2 of 2)

- Each reference orbit has a reference point R
  - For two-body orbit, R moves on Keplerian orbit
  - For three-body orbit, R propagates under influence of both attracting centers (as point masses)
  - S/C orbit perturbations integrated with respect to R
- Associated with each R is a LVLH frame (L) and a formation frame (F)
  - F is useful for formation-flying scenarios
  - F may be offset from R, may be fixed in N or L
- Each spacecraft has one or more Body (B) frames and one LVLH frame (L)
  - L(3) points to nadir, L(2) points to negative orbit normal
  - SC.L is distinct from Orb.L, since SC may be offset from R

Representing Attitude

- There are several ways to represent the rotation between two reference frames
  - Direction Cosines
  - Euler Angles
  - Quaternions (aka Euler Parameters)
  - and more
- They all have their strengths and weaknesses
  - Learn them all!

Strengths and Weaknesses of Attitude Representations

Representation	Strengths	Weaknesses	Best Used For
Direction Cosines	• Work well with vectors • Easy to catenate rotations • Moderately intuitive (dot products) • No singularities	• 9 params for 3 DOF	• Transforming Vectors
Quaternions	• Efficient (4 params for 3 DOF) • No singularities	• Not intuitive	• Propagating Equations of Motion
Euler Angles	• Intuitive • 3 params for 3DOF	• Singularities • 24 Variants	• Input, Output • Gimballed Joints

Notation for Quaternions, DCMs

- The rotation from frame *A* to frame *B* may be described by the direction cosine matrix

$$ {}^{B}C^{A}_{ij} = \hat{b}_i \cdot \hat{a}_j $$

- Given the components of a vector in *A*, its components in *B* may be found by the multiplication

$$ {}^{B}v = {}^{B}C^{A}\,{}^{A}v $$

- In C, we write the DCM as CBA to preserve order of superscripts, eg

```
MxV(CBA,va,vb)
```

- Quaternions are another way to describe rotations. We use a parallel notation:

```
QxV(qba,va,vb)
```

- These and similar conventions promote concise, *unambiguous* code

42 from the Modeler's Perspective

Features

- Multiple spacecraft, anywhere in the solar system
  - Two-body, three-body orbit dynamics
  - One sun, nine planets, 45 major moons
  - Minor bodies (comets and asteroids) added as needed
    - Bennu, Eros, Itokawa, Wirtanen, etc
- Supports precision formation flying
  - Several S/C may be tied to a common reference orbit
  - Encke's method or Euler-Hill equations used to propagate relative orbit states
    - Precision maintained by judicious partitioning of dynamics
      - Add big things to big things, small things to small things
- Clean FSW interface facilitates FSW validation
  - As flight software matures, it can be migrated out of 42
  - Used by GLAST project for independent validation of vendor's (autocoded) GNC flight software

Environment Models

- Planetary Ephemerides
  - From Meeus, “Astronomical Algorithms”
  - Good enough for GNC validation, not intended for mission planning
    - Use GMAT or ODTBX for that
- Gravity Models have coefficients up to 18th order and degree
  - Earth: EGM96
  - Mars: GMM-2B
  - Luna: GLGM2
- Planetary Magnetic Field Models
  - IGRF up to 10th order (Earth only)
  - Tilted offset dipole field
- Earth Atmospheric Density Models
  - MSIS-86 (thanks to John Downing)
  - Jacchia-Roberts Atmospheric Density Model (NASA SP-8021)
  - NRLMSISE00 (Update to MSIS-86, extended down to ground)
- Simple exponential Mars atmosphere density model
  - New models easily incorporated as the state of the art advances

Dynamics Models

- Full nonlinear "6DOF" (actually N-DOF) dynamics
- Attitude Dynamics
  - One or many bodies
    - Tree topology (no kinematic loops)
  - Each body may be rigid or flexible
  - Joints may combine rotational and translational DOFs
    - May be gimballed or spherical
  - Slosh may be modeled as a pendulum (lo-fi, quick to implement and run)
    - 42 may run concurrently with Star-CCM CFD software for hi-fi slosh
  - Wheels embedded in Body[0]
  - Torques from actuators, aerodynamic drag, gravity-gradient, solar radiation pressure, joint torques
- Orbit Dynamics
  - Two- or three-body orbits
  - Encke or Euler-Hill (Clohessy-Wiltshire) for relative orbit motion (good for formation flying, prox ops)
  - Forces from actuators, aerodynamic drag, non-spherical gravity, third-body gravity, solar radiation pressure

The Bleeding Edge

- 42 is under constant development
- Here are some capabilities that are still provisional or under development
  - Contact forces (provisional)
    - Applied to some problems, not robust
  - Self-shadowing (provisional)
    - Passed first sanity checks, but some bugs persist
  - Flight in atmosphere (provisional)
    - Pieces in place, no rigorous test problem yet
  - Fluid slosh using Smoothed Particle Hydrodynamics (under development)
    - Needs parallelization to be practical
  - Interfaces to cFS, COSMOS (under development)
    - cFS is open-source flight software system from GSFC
    - COSMOS is open-source ops (cmd/tlm, etc) from Ball

Conclusion

- 42 is intended to support the ACS design cycle from concept to operations
  - Rapid prototyping for concept studies
  - High fidelity for validation, design
  - Plays well in integration, ops ecologies
- Notation, conventions are the key to building a large software tool over time
- *F* = *ma*. All the rest is just accounting.