

VERIFICATION AND VALIDATION OF MOM6

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<https://marshallward.org/mom6vv>



Verification

Am I building the product right?

Validation

Am I building the right product?

Barry Boehm, *Software Risk Management* (1989)

VERIFICATION

What are the *design specifications* of my model?

- Does it compile on target platforms?
- Are the equations dimensionally consistent?
- Does parallelization change the answers?

Verification is the confirmation of design specifications.

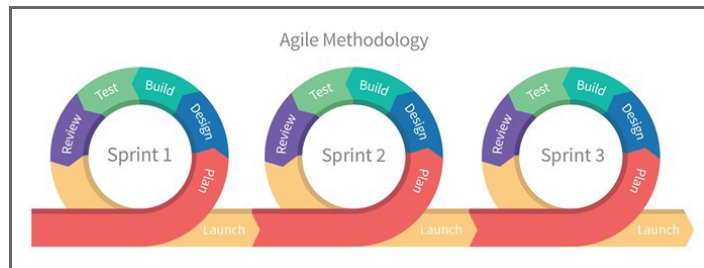
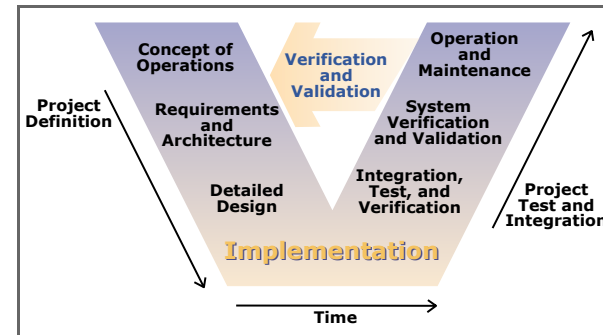
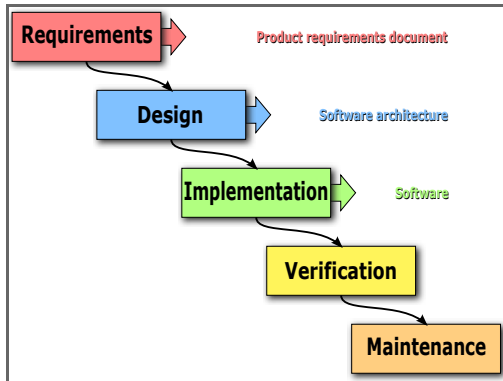
VALIDATION

Does our model meet operational needs?

- Does it produce realistic simulations?
- Are relevant physical features present?
- Can I reproduce my old simulations?

Validation is an assessment of the final product.

V&V IN DEVELOPMENT



MOM6 DEVELOPMENT

NOAA-GFDL / MOM6

Unwatch 49 Unstar 79 Fork 107

Code Issues 101 Pull requests 5 Actions Projects 0 Wiki Security 0 Insights Settings

Modular Ocean Model Edit

ocean-circulation-models ocean-circulation numerical-modelling numerical-modelling fortran Manage topics

7,944 commits 7 branches 0 packages 24 releases 1 environment 42 contributors View license

Branch: dev/gfdl New pull request Create new file Upload files Find file Clone or download

Halberg-NOAA Merge branch fix_NKML_defaults into dev/gfdl	Latest commit f9a1b2 2 days ago
testing	Travis: Arm64 tests; git depth restored; Makefile 19 days ago
config_src	+Rescaled stc_state%frazil and other variables last month
docs	set EXTRACT_ALL to generate call graphs 9 months ago
pkg	Updating pkg 2 years ago
src	+(*)Fix conflicting defaults for NKML 3 days ago
.codecov.yml	Codecov: Set base as parent (target) branch 16 days ago
.gignore	Added testing output to .gignore 9 months ago
.gitlab-ci.yml	Switch to intel/18 on gaea 17 days ago
.gitmodules	restructuring of DA repositories 2 years ago
.readthedocs.yml	Add Read The Docs YAML configuration file 3 years ago
.travis.yml	Travis: Renaming jobs to reflect architecture 19 days ago
LICENSE.md	Update license to LGPLv3 3 years ago
README.md	Replaces in-code license with pointer to LICENSE.md 3 years ago

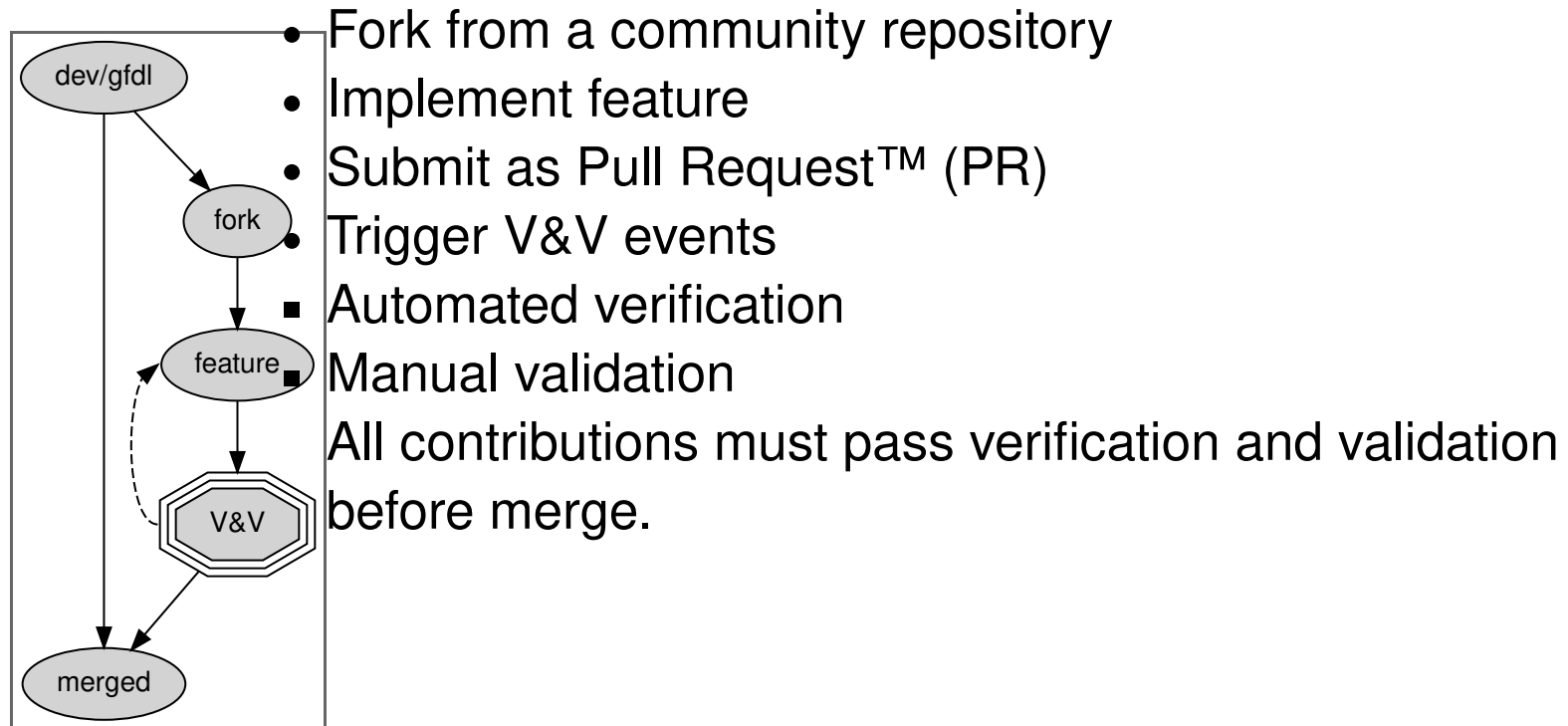
README.md

build passing docs passing codecov 45%

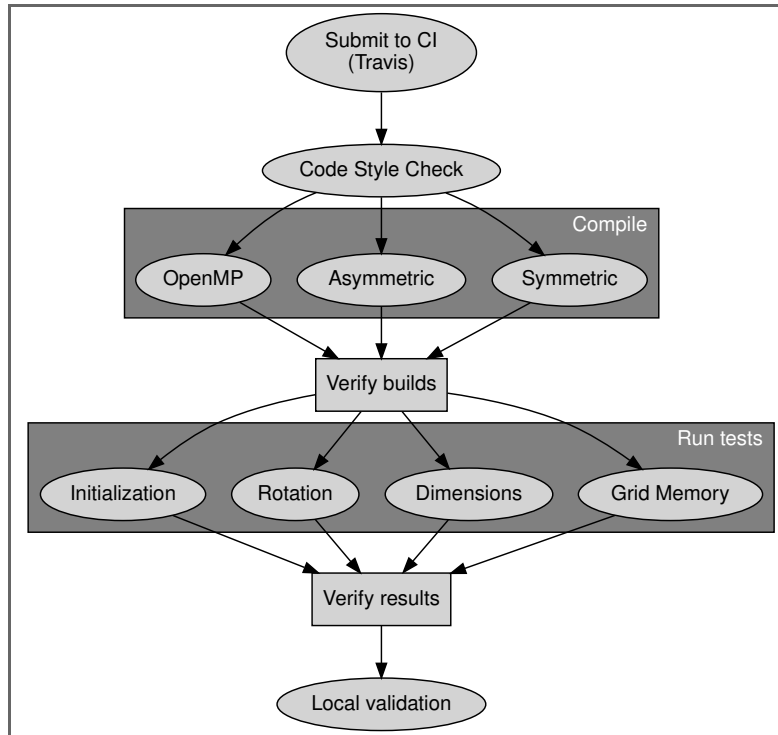
MOM6

This is the MOM6 source code.

V&V IN MOM6



MOM6 VERIFICATION



All changes sent to CI (Travis) for verification

VERIFICATION TESTS

Test Description

grid	Symmetric/Asymmetric memory grids
layout	1×1 and 2×1 domain decomposition
rotation	Index rotation
restart	Restart at mid-run
repro	Optimized reproducible mode
openmp	OpenMP (single-thread)
nan	NaN array initialization
dim	Dimensional scaling

Each test requires bit reproducibility

TESTS IN ACTION

marshallward / MOM6 build passing

Current Branches Build History Pull Requests > Build #419 Job #419.2 More options

✓ **small_log** Makefile: reduced logging, -k support → #419.2 passed Restart job

The Makefile has been modified to reduce the amount of output during Ran for 14 min 17 sec
19 days ago

- Commit 435fa9b
- Compare 2b6d7c6...435fa9b
- Branch small_log

Marshall Ward

View config

```

1 Worker information
6
7 Build system information
167
168
169 Adding APT Sources
595
596 $ git clone --branch=small_log https://github.com/marshallward/MOM6.git
600
601 $ git submodule update --init --recursive
614 Setting environment variables from repository settings
615 $ export CODECOV_TOKEN=[secure]
616
617 Setting environment variables from .travis.yml
618 $ export JOB="Configuration testing"
619 $ export DO_REGRESSION_TESTS=false
620 $ export MKMF_TEMPLATE=linux-ubuntu-xenial-gnu.mk
621
622 $ export TRAVIS_COMPILER=gcc
623 $ export CC=${CC:-gcc}
624 $ export CC_FOR_BUILD=${CC_FOR_BUILD:-gcc}
625 $ gcc --version
626 gcc (Ubuntu 7.5.0-3ubuntu1-18.04) 7.5.0
627 Copyright (C) 2017 Free Software Foundation, Inc.
628 This is free software; see the source for copying conditions. There is NO

```

marshallward / MOM6 build passing

Current Branches Build History Pull Requests > Build #420 Job #420.2 More options

✗ **small_log** Deliberately break many tests → #420.2 failed Restart job

Commit df99204 Ran for 14 min 57 sec
19 days ago

- Compare 435fa9b...df99204
- Branch small_log

Marshall Ward

View config

```

1 Worker information
6
7 Build system information
167
168
169 Adding APT Sources
595
596 $ git clone --branch=small_log https://github.com/marshallward/MOM6.git
600
601 $ git submodule update --init --recursive
614 Setting environment variables from repository settings
615 $ export CODECOV_TOKEN=[secure]
616
617 Setting environment variables from .travis.yml
618 $ export JOB="Configuration testing"
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622 $ export TRAVIS_COMPILER=gcc
623 $ export CC=${CC:-gcc}
624 $ export CC_FOR_BUILD=${CC_FOR_BUILD:-gcc}
625 $ gcc --version
626 gcc (Ubuntu 7.5.0-3ubuntu1-18.04) 7.5.0
627 Copyright (C) 2017 Free Software Foundation, Inc.
628 This is free software; see the source for copying conditions. There is NO
629 warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
630
631 $ cd .testing

```

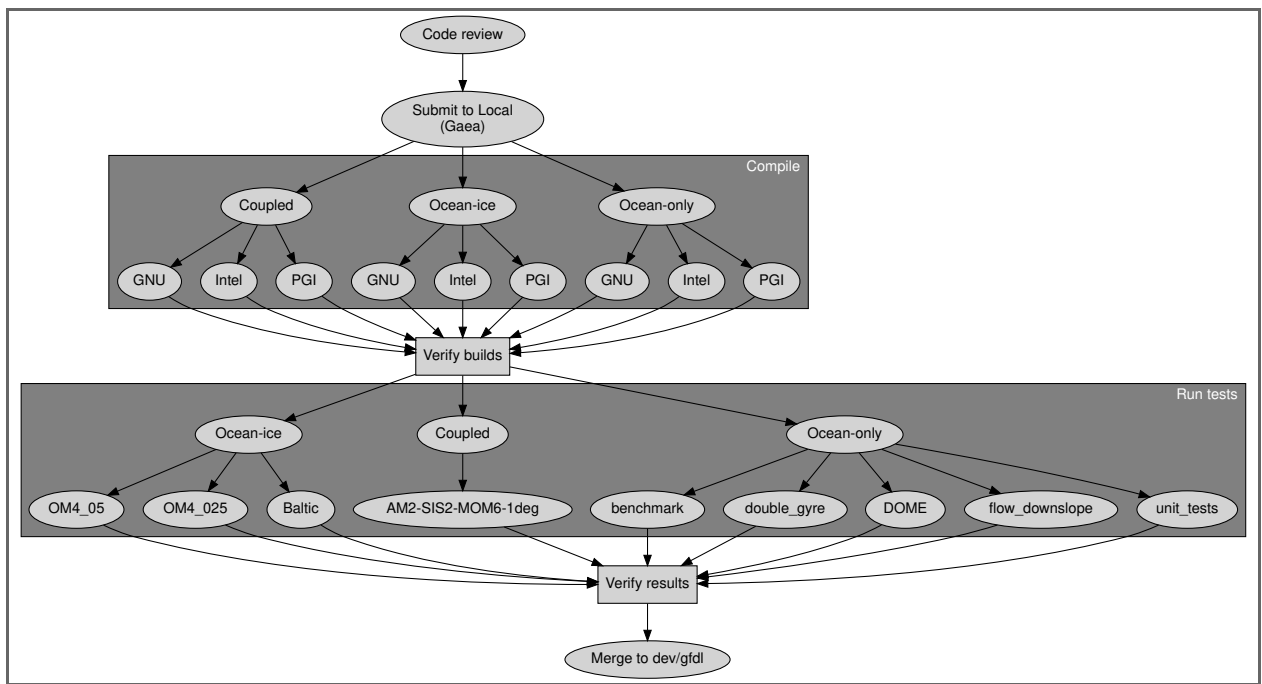

REGRESSIONS

The screenshot displays the Travis CI interface for the NOAA-GFDL / MOM6 repository. The main view shows 'Build #2063' with a 'build passing' status. A pull request #1107 is highlighted with a red bar, indicating a failed build. The build jobs table shows three jobs: #2063.1 (passed), #2063.2 (passed), and #2063.3 (failed).

Job ID	Status	Platform	Architecture	OS	Job Name	Duration
# 2063.1	✓	AMD64	Bionic	</> C	JOB="Code compliance	1 min 28 sec
# 2063.2	✓	AMD64	Bionic	</> C	JOB="Configuration tes	14 min 52 sec
# 2063.3	✗	AMD64	Bionic	</> C	JOB="Regression testin	6 min 51 sec

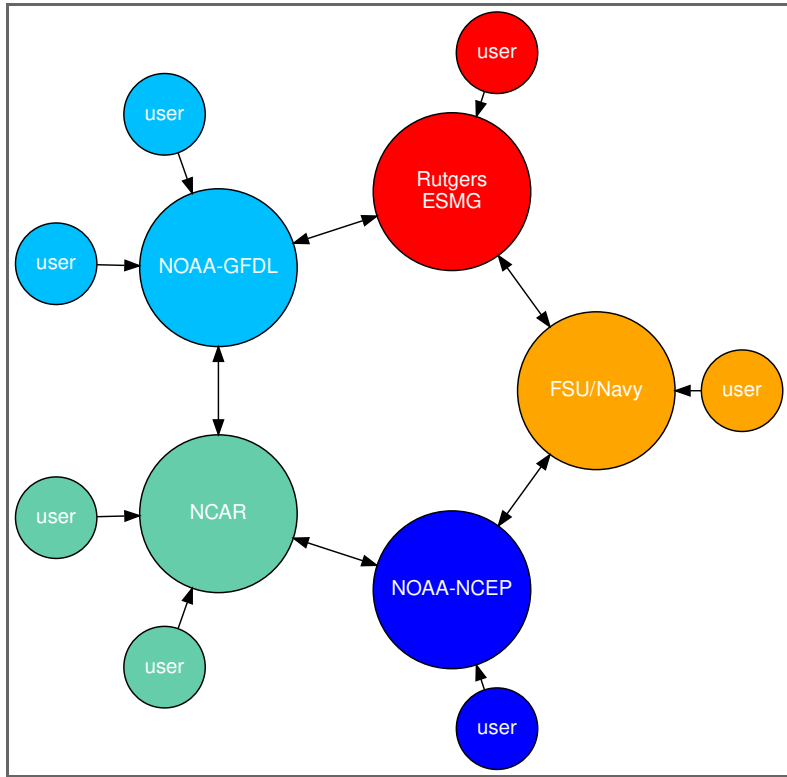
What if we want answers to change?

MOM6 VALIDATION



Current validation includes over 60 tests

HUB VALIDATION



SOLUTION VERIFICATION

ocean.stats:

```

Step,          Day,  Truncs,          Energy/Mass,
Maximum CFL,  Mean Sea Level,  Total Mass,  Mean Salin,
Mean Temp,  Frac Mass Err,  Salin Err,  Temp Err
                [days]                [m2 s-2]
[Nondim]          [m]                [kg]                [PSU]
[degC]            [Nondim]          [PSU]                [degC]
    0,            0.000,            0, En 7.2161166068132286E-27,
CFL 0.00000, SL 1.8190E-12, M 1.39637E+20, S 35.0000,
T 13.3483, Me 0.00E+00, Se 0.00E+00, Te 0.00E+00
    12,           0.500,            0, En 2.7781004671136538E-04,
CFL 0.00011, SL 1.1369E-12, M 1.39637E+20, S 35.0000,
T 13.3484, Me -6.09E-17, Se -3.90E-15, Te -1.17E-15
    24,           1.000,            0, En 2.7734897826598717E-04,
CFL 0.00014, SL 1.8190E-12, M 1.39637E+20, S 35.0000,
T 13.3486, Me 2.89E-17, Se 8.80E-17, Te -2.88E-16

```


Based on global metrics (energy, mass, etc)

DIAGNOSTIC VERIFICATION

chksum_diag:

```
u-point: mean= 1.1239682303793666E-04 min=  
-6.7187595818683776E-03 max= 3.3480219779204019E-02  
ocean_model-u  
u-point: c= 21851 ocean_model-u  
v-point: mean= 1.2076392816784489E-03 min=  
-8.3469699425156359E-03 max= 6.8420831486068704E-03  
ocean_model-v  
v-point: c= 18606 ocean_model-v  
h-point: mean= 3.6490088139048595E+02 min=  
9.9999999999999915E-04 max= 5.6265092225099863E+02  
ocean_model-h  
h-point: c= 18673 ocean_model-h
```

Min, max, mean, bitcount for every diagnostic

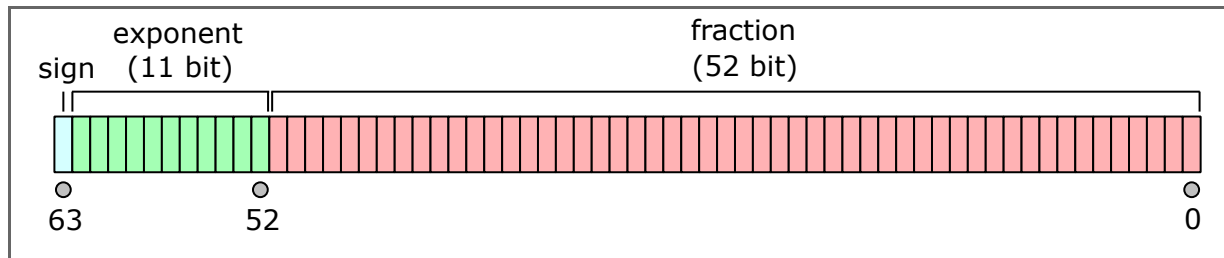
BIT REPRODUCIBILITY

Verification requires bit reproducibility



Identical code and input, different math libraries (c/o **Foone**)

FLOATING POINT REVIEW



$$\phi \equiv (-1)^s \times 2^M \times (1 + \alpha)$$

- Smallest fractional diff: $2^{-52} \approx 2.2 \times 10^{-16}$
- 17 digits to uniquely specify a result

ADDITION ASSOCIATIVITY

What is $10^{-16} + 1 - 1$?

$$(10^{-16} + 1) - 1 = 0$$

$$10^{-16} + (1 - 1) \equiv 10^{-16}$$

Residuals below 2×10^{-16} may be lost.

MORE ADDITION EXAMPLES

Let $s = 1 + 2 \times 10^{-16}$. What is $(s + 1) - 1$?

$$s + 1 = 2$$

$$(s + 1) - 1 = 1 \neq s$$

Manipulation of s shifted the least resolvable value.

MULTIPLICATION ASSOCIATIVITY

If $a = b = 1.5$, and $c = 1 + 2^{-52}$, then

$$(a \times b) \times c \equiv 2.25 + 2^{-51}$$

$$a \times (b \times c) \equiv 2.25 + 2^{-50}$$

(Actual results depend on rounding rules)

SAMPLE PROGRAM

```
program rounding
  use iso_fortran_env, only : real64
  implicit none

  real(kind=real64) :: a, b, c

  a = 1.5
  b = 1.5
  c = 1.000000000000000002_real64

  print '(a, es23.17)', "(a * b) * c = ", (a * b) * c
  print '(a, es23.17)', "a * (b * c) = ", a * (b * c)
end program rounding
```


INTEGRITY OF PARENTHESES

V&V requires integrity of parentheses

GCC Fortran

```
gfortran -fprotect-parens ... # default
gfortran -Ofast ... # Sets -fno-protect-
parens
```

Intel Fortran

```
ifort -assume protect-parens # Not default
```

Note: Fortran requires this!

DIVISION PERFORMANCE

Minimize division operations:

```
x = a / b / c          ! Bad
x = a / (b * c)       ! Good

y = 1. / (1. + 1./c)  ! Bad
y = c / (c + 1.)     ! Good
```

Store common divisions:

```
I_dx = 1.0 / dx
dudx = I_dx * (u(i+1) - u(i))
dvdx = I_dx * (v(i+1) - v(i))
```

Divisions are slower and more unpredictable

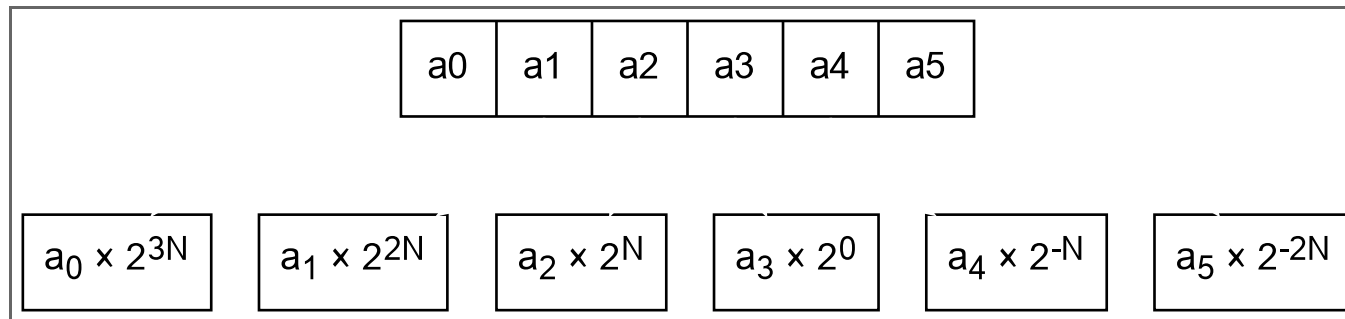
PARALLEL SUMMATION

How to compute reproducible means or global sums?

- Enforce ordering

$$\sum \phi = (\phi_1 + (\phi_2 + (\phi_3 + \dots)))$$

- Fixed-precision arithmetic



ASSOCIATIVE SCALING

Recall the floating point format

$$\phi \equiv (-1)^s \times 2^M \times (1 + \alpha)$$

Power-of-two multiplication is associative

$$2^N \times \phi \times 2^{-N} \equiv \phi$$

DIMENSION SCALING

Fields rescaled by dimensions should be invariant

$$u^{n+1} = u^n + \Delta t \times \mathcal{F}$$
$$2^{L-T} u^{n+1} = 2^{L-T} u^n + 2^T \Delta t \times 2^{L-2T} \mathcal{F}$$

DIMENSIONAL FACTORS

Unit	Scaling	Name
s	T	Time
m	L	Horizontal length
m	H	Layer thickness
m	Z	Vertical length
kg/m ³	R	Density
J/kg	Q	Enthalpy

DEFINING DIMENSIONS

Input parameters

```
call get_param(... , "DT", ... , scale=US%s_to_T)
```

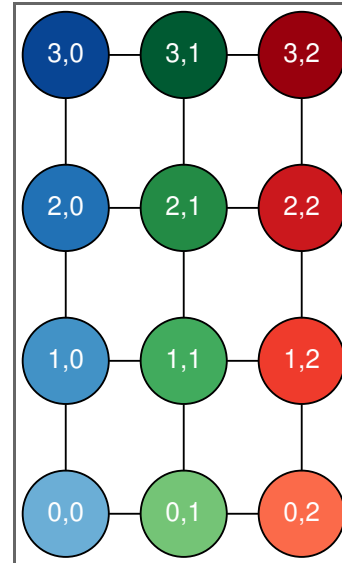
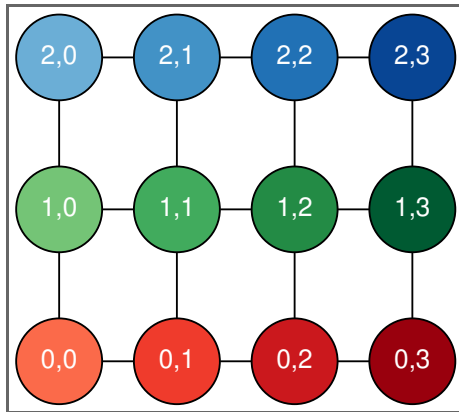
Explicit constants

```
eps_vel = 1.0e-10 * US%m_s_to_L_T  
ustar = 0.01 * US%m_to_Z * US%T_to_s
```

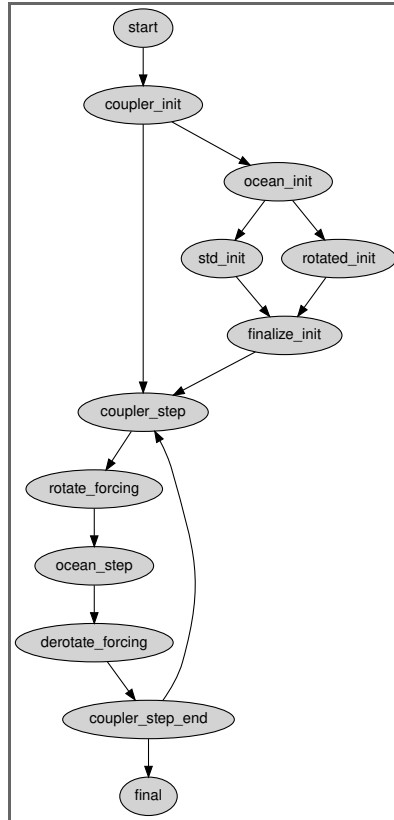
Diagnostic registration

```
call register_diag_field(..., "u", ... ,  
conversion=US%L_T_to_m_s)
```


INDEX ROTATION



ROTATION INVARIANCE



Solutions must be invariant to **index rotation**,
e.g.:

$$\phi(i', j') = \phi(j, N - i)$$

Both *fields* and *coordinates* are remapped.
Note: u and v are velocities along i and j !

ROTATIONAL CONSISTENCY

```

beta_topo_x = -CS%MEKE_topographic_beta * Fath * 0.5 *
( &
      (G%bathyT(i+1,j)-G%bathyT(i,j)) *
G%IdxCu(I,j) &
      / max(G%bathyT(i+1,j),G%bathyT(i,j),
GV%H_subroundoff) &
      +      (G%bathyT(i,j)-G%bathyT(i-1,j)) *
G%IdxCu(I-1,j) &
      / max(G%bathyT(i,j),G%bathyT(i-1,j),
GV%H_subroundoff) )

```

```

beta_topo_y = -CS%MEKE_topographic_beta * Fath * 0.5 *
( &
      (G%bathyT(i,j+1)-G%bathyT(i,j)) *
G%IdyCv(i,J) &
      / max(G%bathyT(i,j+1),G%bathyT(i,j),
GV%H_subroundoff) + &
      (G%bathyT(i,j)-G%bathyT(i,j-1)) *
G%IdyCv(i,J-1) &

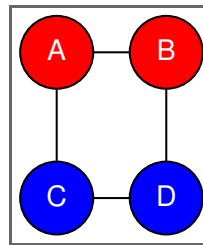
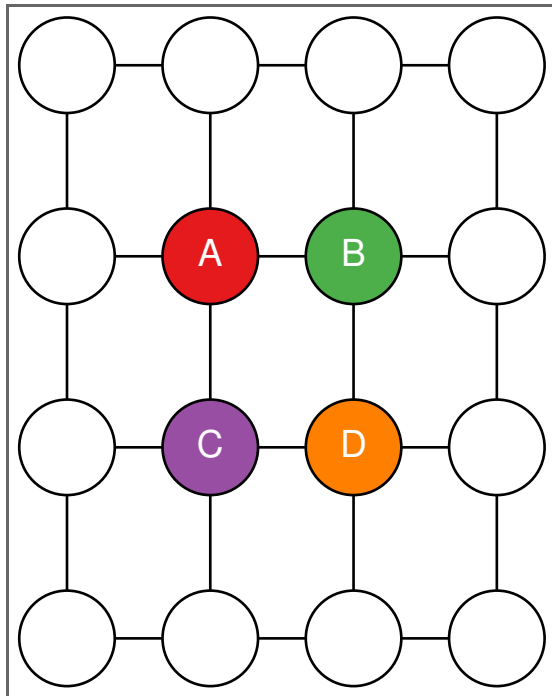
```

```
    / max(G%bathyT(i, j), G%bathyT(i, j-1),  
    GV%H_subroundoff) )
```

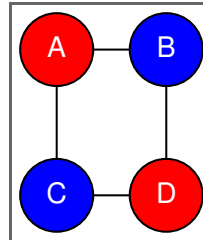
Index rotation ensures directional consistency

INVARIANT STENCILS

$$\phi_{i,j}^{(c)} = \frac{1}{4} (\phi_A + \phi_B + \phi_C + \phi_D)$$



$$\frac{1}{4} ((\phi_A + \phi_B) + (\phi_C + \phi_D))$$



$$\frac{1}{4} ((\phi_A + \phi_D) + (\phi_B + \phi_C))$$

ROTATIONAL ORDERING

When all else fails, reorder the algorithm:

```
subroutine advect_tracer(...)
  ! ...
  x_first = modulo(turns, 2) == 1
  if (x_first) then
    call advect_x(...)
    call advect_y(...)
  else
    call advect_y(...)
    call advect_x(...)
  endif
end subroutine advect_tracer
```

SUMMARY

- MOM6 test suite:
 - Verification of design requirements
 - Universal invariance rules
 - Validation of solutions
 - Site-specific regression tests
- Bit reproducibility is essential, and achievable!
- Over 40 bugs have been detected and fixed

DIMENSIONAL SCALING EXAMPLE

<https://github.com/NOAA-GFDL/MOM6/pull/921>

```
Kd_lay(i, j, k-1) = Kd_lay(i, j, k-1) + 0.5**KS_extra(i, K)  
Kd_lay(i, j, k)   = Kd_lay(i, j, k)   + 0.5**KS_extra(i, K)
```

... + $\left(\frac{1}{2}\right)^{k_S}$?

ROTATIONAL EXAMPLE

<https://github.com/NOAA-GFDL/MOM6/pull/1050>

```
subroutine thickness_diffuse_full
  !...
  Work_u(I,j) = Work_u(I,j) + G_scale * (...)
  Work_v(i,J) = Work_v(i,J) - G_scale * (...)
  !...
end subroutine thickness_diffuse_full
```

INDEXING EXAMPLE

Assumed 1-based start index

```
subroutine register_time_deriv(...)
  real, dimension(:,:,:), target :: f_ptr
  real, dimension(:,:,:), target :: deriv_ptr
  ! ...
end subroutine register_time_deriv
```

Fails for 0-based symmetric memory grids!

ANOTHER INDEXING EXAMPLE

78d2dc3ee9a018f30bc666bd574e21fb7786403d

Extended domain to accommodate symmetric grids:

```
do J=js,je ; do i=is,ie
  h_vel = 0.5*((htot_fast(i,j) + htot_fast(i+1,j)) +
h_neglect)
  uDml_diag(I,j) = uDml_diag(I,j) / (0.01*h_vel) *
G%IdyCu(I,j) * (PSI(0.)-PSI(-.01))
enddo ; enddo
```

```
do J=js,je ; do i=is-1,ie
  h_vel = 0.5*((htot_fast(i,j) + htot_fast(i+1,j)) +
h_neglect)
  uDml_diag(I,j) = uDml_diag(I,j) / (0.01*h_vel) *
G%IdyCu(I,j) * (PSI(0.)-PSI(-.01))
enddo ; enddo
```


DEVELOPMENT GUIDELINES

1. Use parentheses!
 1. Are they honored?
 2. Am I preserving residuals?
2. Use `reproducing_sum()`
 1. Even better: Don't do global sums!
3. Assign dimensions
4. Use rotationally invariant stencils
5. Test early and often