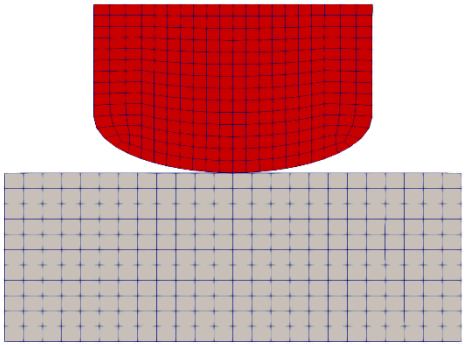
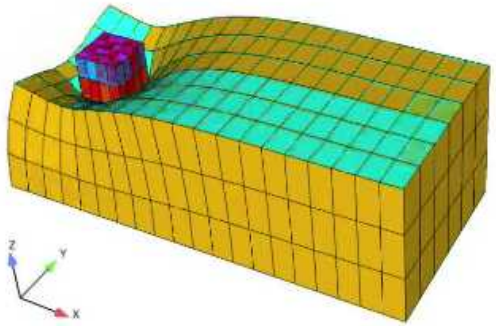
SAND2017-12048PE





SIERRA/SM Implicit Contact: Troubleshooting

November 2017

SIERRA/SolidMechanics Team

Outline

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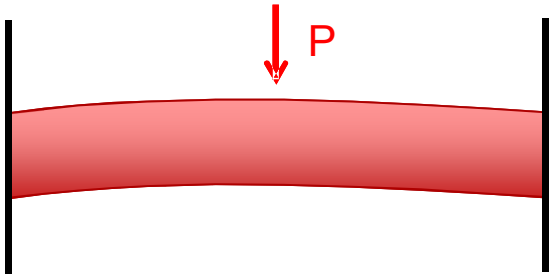
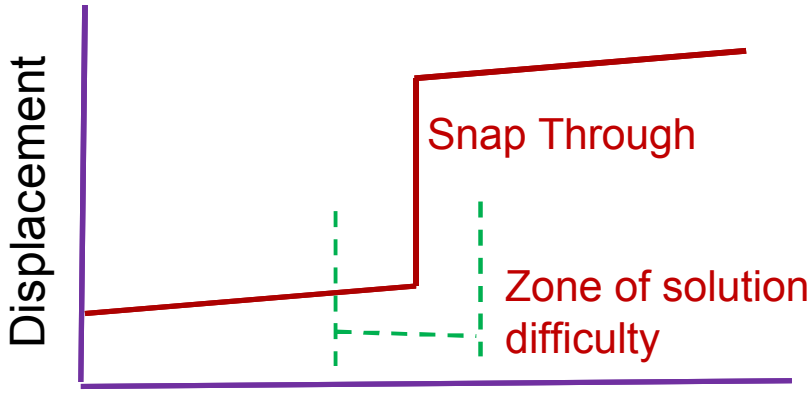
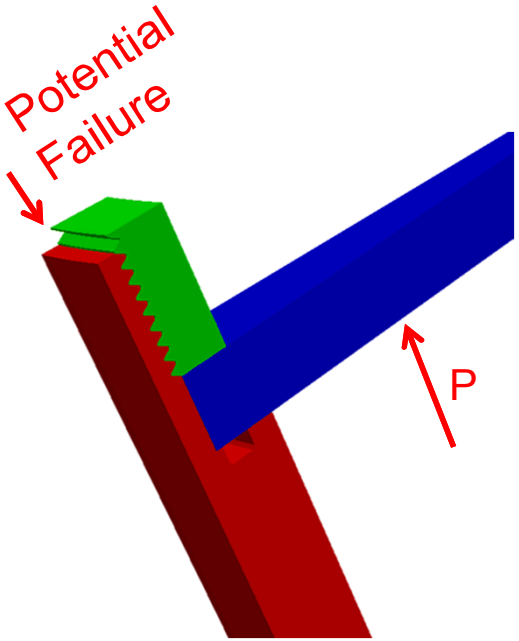
- Revisit common pitfalls for implicit quasi-statics
- Revisit recommended solver settings for contact problems
- Revisit logfile and expand upon logfile-based debugging
  - Linear Solver
  - Control Contact
- Other debugging tools
  - Visualization
  - Iteration plotting
  - Problem simplification/isolation
  - *Etc.*
- Debugging example problems
  - Resistance forge weld
  - Pressurized can with threaded lid
  - Stiff square indenting into soft material
- Summary

Common Pitfalls for Implicit Quasi-statics

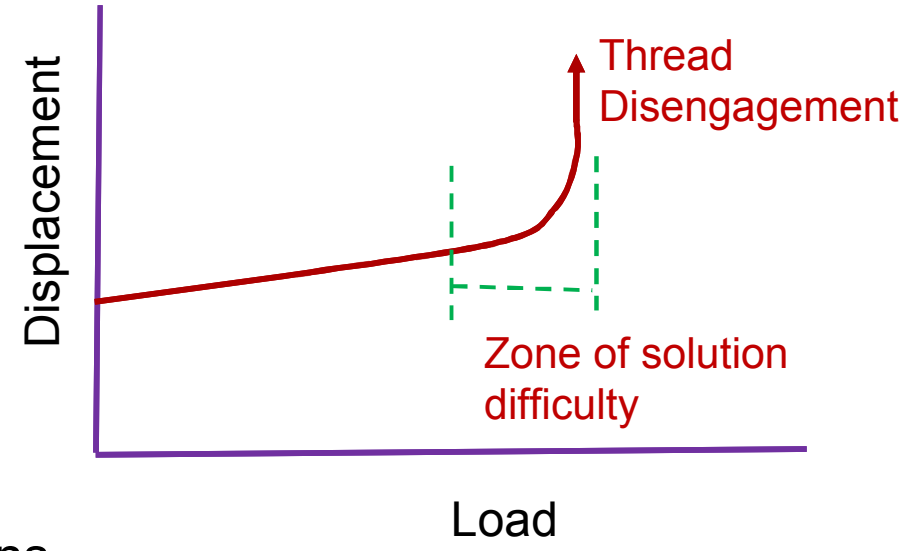


Buckling

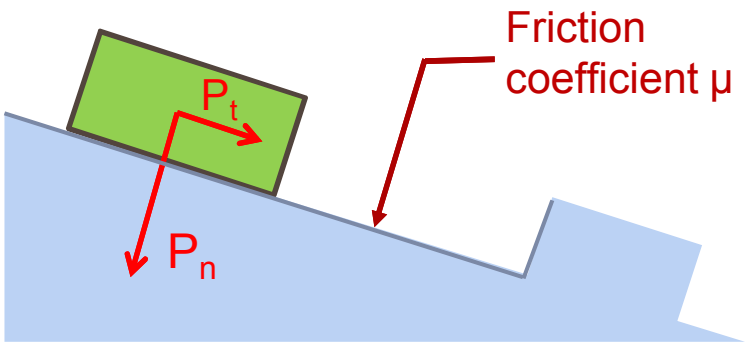




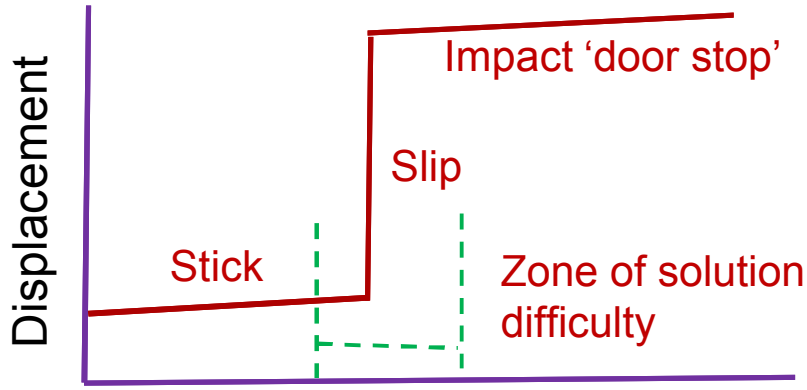
Nearby Failure Conditions



Common Pitfalls for Implicit Quasi-statics



Stick/Slip



P_t

- Rate-dependent material models
- Multiple constraints on nodes (*e.g.* where contact intersects kinematic BC's)
- Sharp material non-linearity and/or incompressible materials
- P-delta effects
- Poorly-shaped elements in input mesh
- Initial overlap in input mesh (use "Overlap Removal"; inspect mesh after)
- Thermal-Mechanical coupling

Recommended Robust Contact Solver Settings

```
begin solver
  begin loadstep predictor
    scale factor = 0.0 0.0
  end

  begin control contact
    target relative residual = 1.0e-4
  end

  begin cg
    target relative residual = 1.0e-5
    acceptable relative residual = 1.0
    maximum iterations = 100
    begin full tangent preconditioner
      tangent diagonal scale = 1.0e-6
    end
   end
 end
```

Turns off loadstep predictor (can cause more harm than good)

Usable range: 1.0e-2 to 1.0e-8

~10X spread recommended

Allows constraints to change between captured and released

Provides limited resilience to rigid body modes

Log File Debugging

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The log file should be a primary source for debugging

- Look for all error and/or warning messages
- If using adaptive time stepping, look for cutbacks
  - This is often where the trouble started: inverted or poorly-shaped elements, contact lost, loss of static equilibrium, *etc.*
- Look for acceptable tolerances (“<A”) achieved instead of target tolerances (“<T”)
  - Why?
  - Can it be avoided?

Log File Debugging: Linear Solve

```
================================================================================================================
Begin load step =     0 Solution period Apst_Procedure_p1 is   0.0% complete
        Old Time        Time Step          New Time         Stop Time      CPU Time(s)     Wall Time(s)
      0.0000e+00      1.0000e+00       1.0000e+00       1.0000e+00       8.1388e-01       2.0306e-02
----------------------------------------------------------------------------------------------------------------
                              LINEAR        MP                          RELATIVE      EXTERNAL
                         RBM    ITER       ITER      RESIDUAL          RESIDUAL      REFERENCE       ENERGY DISPLACEMENT
----------------------------------------------------------------------------------------------------------------
                           -       -          0     1.534e+11      9.714e-01      1.579e+11             -            -
                           0    U  1          1     5.045e+10      6.957e-01      7.252e+10     5.301e+08     7.486e+00
                           0       1          2     2.802e+10      4.079e-01      6.870e+10     1.865e+08     5.993e-01
                           0       1          3     8.507e+09      1.272e-01      6.690e+10     1.025e+06     1.696e-01
                           0       1          4     1.399e+09      2.112e-02      6.621e+10     3.374e+03     1.777e-03
                           0       1          5     6.609e+08      9.969e-03      6.630e+10     6.803e+03     1.677e-04
                           0       1          6     2.010e+08      3.031e-03      6.632e+10     8.050e+01     4.362e-05
                           0       1          7     7.116e+07      1.073e-03      6.631e+10     4.210e-01     9.116e-06
                           0       1          8     3.546e+07      5.348e-04      6.630e+10     4.855e-02     1.109e-06
                           0       1          9     1.414e+07      2.133e-04      6.631e+10     1.567e-02     2.213e-07
                           0       1         10     4.935e+06      7.443e-05<T    6.631e+10     1.533e-03     2.833e-08
```

Rigid body modes

Tangent re-calculation ("U"pdate)

2-norm of nodal force imbalance

Residual normalized by reference quantity

convergence status

Reference quantity (external force, energy, *etc*.)

Alternative Convergence Criteria

Log File Debugging: Linear Solve

```
================================================================================================================
Begin load step =     0 Solution period Apst_Procedure_p1 is   0.0% complete
        Old Time        Time Step          New Time        Stop Time      CPU Time(s)     Wall Time(s)
      0.0000e+00      1.0000e+00        1.0000e+00      1.0000e+00       8.1388e-01       2.0306e-02
----------------------------------------------------------------------------------------------------------------
                                LINEAR       MP                    RELATIVE     EXTERNAL
                          RBM   ITER       ITER      RESIDUAL      RESIDUAL     REFERENCE       ENERGY DISPLACEMENT
----------------------------------------------------------------------------------------------------------------
                                  -          0     1.534e+11     9.714e-01     1.579e+11            -            -
                          0   U   1          1     5.045e+10     6.957e-01     7.252e+10     5.301e+08    7.486e+00
                          0       1          2     2.802e+10     4.079e-01     6.870e+10     1.865e+08    5.993e-01
                          0       1          3     8.507e+09     1.272e-01     6.690e+10     1.025e+06    1.696e-01
                          0       1          4     1.399e+09     2.112e-02     6.621e+10     3.374e+03    1.777e-03
                          0       1          5     6.609e+08     9.969e-03     6.630e+10     6.803e+03    1.677e-04
                          0       1          6     2.010e+08     3.031e-03     6.632e+10     8.050e+01    4.362e-05
                          0       1          7     7.116e+07     1.073e-03     6.631e+10     4.210e-01    9.116e-06
                          0       1          8     3.546e+07     5.348e-04     6.630e+10     4.855e-02    1.109e-06
                          0       1          9     1.414e+07     2.133e-04     6.631e+10     1.567e-02    2.213e-07
                          0       1         10     4.935e+06     7.443e-05<T   6.631e+10     1.533e-03    2.833e-08
```

Rigid Body Modes (RBM's):

- If =0: no rigid body modes detected by solver
- If >0:
  - Add BC's to constrain free DOF's in one or more element blocks
  - Use ITERATION PLOT to find any missed RBM's
  - If loss of contact, element death, *etc*. cause static problem to become dynamic: try using explicit dynamics, implicit dynamics, or control damped solve

Log File Debugging: Linear Solve

```
================================================================================================================
Begin load step =     0 Solution period Apst_Procedure_p1 is    0.0% complete
        Old Time        Time Step        New Time        Stop Time      CPU Time(s)     Wall Time(s)
      0.0000e+00      1.0000e+00      1.0000e+00      1.0000e+00       8.1388e-01       2.0306e-02
----------------------------------------------------------------------------------------------------------------
                            LINEAR       MP                      RELATIVE      EXTERNAL
                       RBM    ITER      ITER      RESIDUAL      RESIDUAL     REFERENCE       ENERGY DISPLACEMENT
----------------------------------------------------------------------------------------------------------------
                         -       -         0     1.534e+11     9.714e-01     1.579e+11            -            -
                         0       U         1     5.045e+10     6.957e-01     7.252e+10     5.301e+08    7.486e+00
                         0       1         2     2.802e+10     4.079e-01     6.870e+10     1.865e+08    5.993e-01
                         0       1         3     8.507e+09     1.272e-01     6.690e+10     1.025e+06    1.696e-01
                         0       1         4     1.399e+09     2.112e-02     6.621e+10     3.374e+03    1.777e-03
                         0       1         5     6.609e+08     9.969e-03     6.630e+10     6.803e+03    1.677e-04
                         0       1         6     2.010e+08     3.031e-03     6.632e+10     8.050e+01    4.362e-05
                         0       1         7     7.116e+07     1.073e-03     6.631e+10     4.210e-01    9.116e-06
                         0       1         8     3.546e+07     5.348e-04     6.630e+10     4.855e-02    1.109e-06
                         0       1         9     1.414e+07     2.133e-04     6.631e+10     1.567e-02    2.213e-07
                         0       1        10     4.935e+06     7.443e-05<T   6.631e+10     1.533e-03    2.833e-08
```

Tangent Update:

- Benefits: much better convergence rate when problem is non-linear
- Drawbacks: computationally expensive
- When to try more frequent updates: no RBM's but residual is stagnating
- Indicator that it is beneficial: residual drops significantly at each update
- Tips:
  - Try changing ITERATION UPDATE: controls tangent update frequency
  - Try changing SMALL NUMBER OF ITERATIONS: avoids updates at start of load step when previous load step converged quickly

Log File Debugging: Linear Solve

```
================================================================================================================
Begin load step =     0 Solution period Apst_Procedure_p1 is   0.0% complete
        Old Time        Time Step        New Time        Stop Time      CPU Time(s)     Wall Time(s)
      0.0000e+00      1.0000e+00      1.0000e+00      1.0000e+00       8.1388e-01       2.0306e-02
----------------------------------------------------------------------------------------------------------------
                            LINEAR       MP                    RELATIVE     EXTERNAL
                       RBM    ITER      ITER      RESIDUAL      RESIDUAL     REFERENCE       ENERGY DISPLACEMENT
----------------------------------------------------------------------------------------------------------------
                         -       -         0     1.534e+11     9.714e-01     1.579e+11            -            -
                         0   U   1         1     5.045e+10     6.957e-01     7.252e+10     5.301e+08    7.486e+00
                         0       1         2     2.802e+10     4.079e-01     6.870e+10     1.865e+08    5.993e-01
                         0       1         3     8.507e+09     1.272e-01     6.690e+10     1.025e+06    1.696e-01
                         0       1         4     1.399e+09     2.112e-02     6.621e+10     3.374e+03    1.777e-03
                         0       1         5     6.609e+08     9.969e-03     6.630e+10     6.803e+03    1.677e-04
                         0       1         6     2.010e+08     3.031e-03     6.632e+10     8.050e+01    4.362e-05
                         0       1         7     7.116e+07     1.073e-03     6.631e+10     4.210e-01    9.116e-06
                         0       1         8     3.546e+07     5.348e-04     6.630e+10     4.855e-02    1.109e-06
                         0       1         9     1.414e+07     2.133e-04     6.631e+10     1.567e-02    2.213e-07
                         0       1        10     4.935e+06     7.443e-05<T   6.631e+10     1.533e-03    2.833e-08
```

Solution Iterations:

- When to increase max iterations: residual still dropping at max
- When to decrease max iterations: residual bottoming out before max
- When to use min iterations >0: residual <T but still substantially decreasing
  (in this case, increasing min iterations can improve convergence of subsequent steps)

Log File Debugging: Linear Solve

```
================================================================================================================
Begin load step =     0 Solution period Apst_Procedure_p1 is   0.0% complete
        Old Time        Time Step        New Time        Stop Time      CPU Time(s)     Wall Time(s)
      0.0000e+00      1.0000e+00      1.0000e+00      1.0000e+00       8.1388e-01       2.0306e-02
----------------------------------------------------------------------------------------------------------------
                              LINEAR       MP                    RELATIVE     EXTERNAL
                         RBM    ITER      ITER      RESIDUAL      RESIDUAL     REFERENCE       ENERGY DISPLACEMENT
----------------------------------------------------------------------------------------------------------------
                           -       -         0     1.534e+11     9.714e-01     1.579e+11            -            -
                           0   U   1         1     5.045e+10     6.957e-01     7.252e+10     5.301e+08     7.486e+00
                           0       1         2     2.802e+10     4.079e-01     6.870e+10     1.865e+08     5.993e-01
                           0       1         3     8.507e+09     1.272e-01     6.690e+10     1.025e+06     1.696e-01
                           0       1         4     1.399e+09     2.112e-02     6.621e+10     3.374e+03     1.777e-03
                           0       1         5     6.609e+08     9.969e-03     6.630e+10     6.803e+03     1.677e-04
                           0       1         6     2.010e+08     3.031e-03     6.632e+10     8.050e+01     4.362e-05
                           0       1         7     7.116e+07     1.073e-03     6.631e+10     4.210e-01     9.116e-06
                           0       1         8     3.546e+07     5.348e-04     6.630e+10     4.855e-02     1.109e-06
                           0       1         9     1.414e+07     2.133e-04     6.631e+10     1.567e-02     2.213e-07
                           0       1        10     4.935e+06     7.443e-05<T   6.631e+10     1.533e-03     2.833e-08
```

Convergence Status:

- When to tighten target: residual still dropping; or, later step fails to converge
- When to loosen target: current target is small and never achieved
- When to tighten acceptable: CG is outer loop of single-/multi-level solve and observably bad solution(s) accepted; later step fails
- When to loosen acceptable: CG is inner loop of multi-level solve (*e.g.* to avoid erroring-out when control contact has a bad model problem)

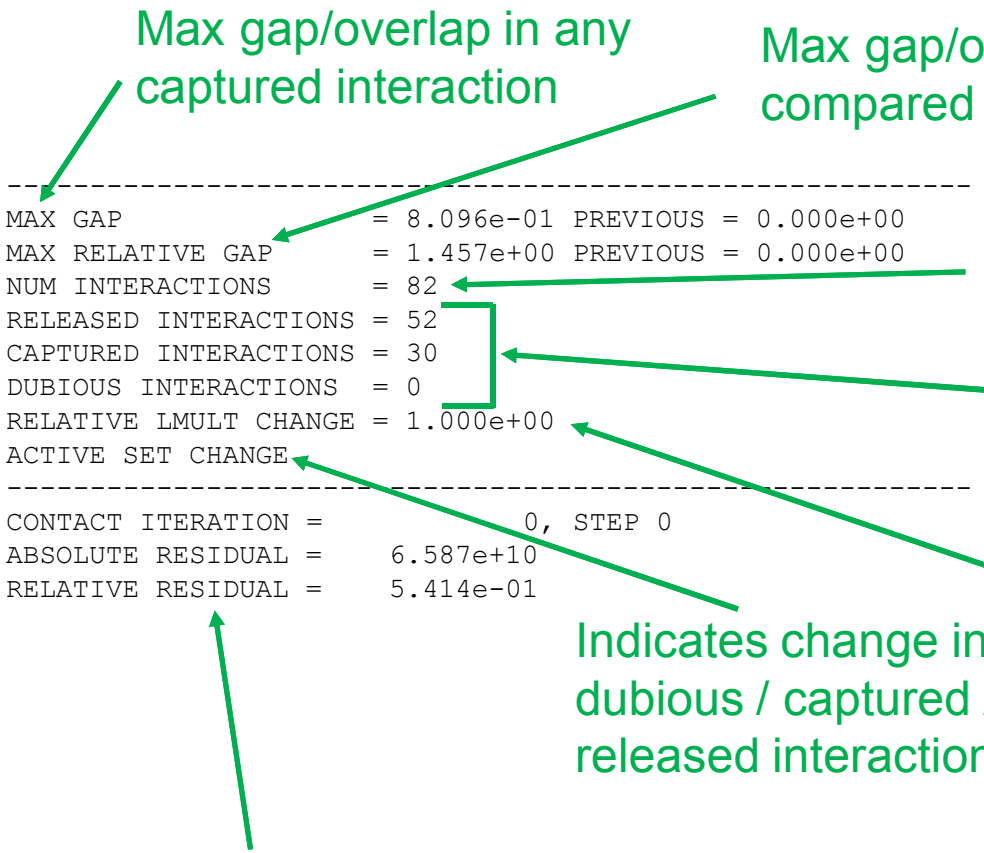
Log File Debugging: Linear Solve

RBM	LINEAR ITER	MP ITER	RESIDUAL	RELATIVE RESIDUAL	EXTERNAL REFERENCE	ENERGY	DISPLACEMENT
0	1	1	2.616e-06	2.677e-02	9.772e-05	4.940e-24	7.156e-34
0	1	2	2.616e-06	2.677e-02	9.772e-05	4.940e-24	7.156e-34
0	1	3	2.616e-06	2.677e-02	9.772e-05	4.940e-24	7.156e-34
0	1	4	2.616e-06	2.677e-02	9.772e-05	4.940e-24	7.156e-34
0	1	5	2.616e-06	2.677e-02	9.772e-05	4.940e-24	7.156e-34

Residual / Relative Residual:

- If stagnating at a large value:
  - Another indicator of potential RBM's
  - Add BC's to constrain free DOF's in one or more element blocks
  - Use ITERATION PLOT to find any missed RBM's
  - If loss of contact, element death, *etc*. cause static problem to become dynamic: try using explicit dynamics, implicit dynamics, or control damped solve

Log File Debugging: Control Contact



Log File Debugging: Control Contact

```
------------------------------------------------------------
MAX GAP                = 8.096e-01 PREVIOUS = 0.000e+00
MAX RELATIVE GAP       = 1.457e+00 PREVIOUS = 0.000e+00
NUM INTERACTIONS       = 82
RELEASED INTERACTIONS = 52
CAPTURED INTERACTIONS = 30
DUBIOUS INTERACTIONS   = 0
RELATIVE LMULT CHANGE = 1.000e+00
ACTIVE SET CHANGE
------------------------------------------------------------
CONTACT ITERATION =            0, STEP 0
ABSOLUTE RESIDUAL =    6.587e+10
RELATIVE RESIDUAL =    5.414e-01
```

Max Gap / Max Relative Gap; Lagrange Multiplier Change:

- If oscillating or stagnating at a large value:
  - Use smaller load step
  - Eliminate discontinuous or large changes in BC's
  - Evaluate log file and visualize previous load steps to see if the cause is a previously poor contact solution
  - Try solver settings that help avoid inherently discontinuous behavior of contact: *e.g.* Lagrange multiplier settings in control contact, AL penalty factor in contact interactions

Log File Debugging: Control Contact

```
------------------------------------------------------------
MAX GAP                = 8.096e-01 PREVIOUS = 0.000e+00
MAX RELATIVE GAP       = 1.457e+00 PREVIOUS = 0.000e+00
NUM INTERACTIONS       = 82
RELEASED INTERACTIONS  = 52
CAPTURED INTERACTIONS  = 30
DUBIOUS INTERACTIONS   = 0
RELATIVE LMULT CHANGE  = 1.000e+00
ACTIVE SET CHANGE
------------------------------------------------------------
CONTACT ITERATION =            0, STEP 0
ABSOLUTE RESIDUAL =    6.587e+10
RELATIVE RESIDUAL =    5.414e-01
```

Interactions:

- If # dubious interactions never converges to zero and/or, # released/captured interactions continuously change over many contact iterations:
  - Use smaller load step, smoother BC's, different AL settings
  - Evaluate log file and visualize previous load steps to see if the cause is a previously poor contact solution
  - Previously static contact solution could be going dynamic: try explicit dynamics, implicit dynamics, more BC's to maintain static equilibrium, and/or control damped solve

Log File Debugging: Control Contact

```
------------------------------------------------------------
MAX GAP                = 8.096e-01 PREVIOUS = 0.000e+00
MAX RELATIVE GAP       = 1.457e+00 PREVIOUS = 0.000e+00
NUM INTERACTIONS       = 82
RELEASED INTERACTIONS  = 52
CAPTURED INTERACTIONS  = 30
DUBIOUS INTERACTIONS   = 0
RELATIVE LMULT CHANGE  = 1.000e+00
ACTIVE SET CHANGE
-------                ----------------------------------
CONTACT ITERATION =              0, STEP 0
ABSOLUTE RESIDUAL =     6.587e+10
RELATIVE RESIDUAL =     5.414e-01
```

Contact Iterations:

- Reasonable # of iterations: ~5 to ~50
- When to increase max. iterations:
  - Residual still steadily decreasing at max. iterations
  - Contacts are unstable or frequently changing over time
  - Other aspects of problem are temporally non-linear: boundary conditions, thermal conditions, plasticity, failure, …
- How to decrease iterations necessary for convergence:
  - Smaller load step size
  - Come into current load step with a good initial state (evaluate solutions from previous load steps)

Log File Debugging: Control Contact

```
------------------------------------------------------------
MAX GAP                = 8.096e-01 PREVIOUS = 0.000e+00
MAX RELATIVE GAP       = 1.457e+00 PREVIOUS = 0.000e+00
NUM INTERACTIONS       = 82
RELEASED INTERACTIONS  = 52
CAPTURED INTERACTIONS  = 30
DUBIOUS INTERACTIONS   = 0
RELATIVE LMULT CHANGE  = 1.000e+00
ACTIVE SET CHANGE
------------------------------------------------------------
CONTACT ITERATION =              0, STEP 0
ABSOLUTE RESIDUAL =     6.587e+10
RELATIVE RESIDUAL =     5.414e-01
```

Absolute / Relative Residual:

- Recommendation is to place Control Contact at the outer-most loop (highest level) of the multi-level solve
- Therefore, these residuals represent the quality of the solution of each load step
    - This impacts: solution state and contact interactions used for subsequent load steps, amount of gap/overlap, *etc.*

Other Debugging Tools

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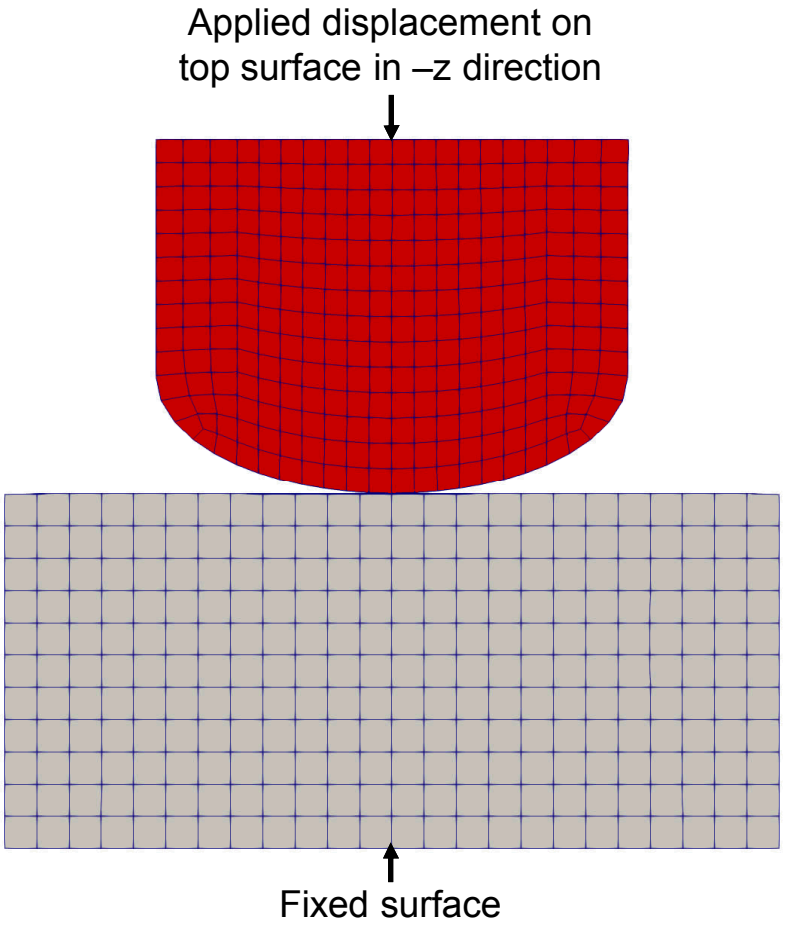
Every problem is different but almost all require one or more of the following in addition to log file parsing:

- Visualization. What to look for:
  - Unintended gaps and overlaps
  - Objects passing through each other where contact is expected
  - Non-smooth contact_status and/or contact_force fields
- Use `ITERATION PLOT` in solver command blocks
  - This outputs fields for each solution iteration
  - Look for when & where the problem is first going awry
- Try explicit dynamics to separate implicit solver issues from other issues: contact, BC's, mesh, *etc.*
- Output mesh after INITIAL OVERLAP REMOVAL to detect possible poorly-shaped or inverted elements from the removal process
- Problem simplification/isolation: coarsen mesh, remove blocks, use elastic materials, create restart checkpoints, *etc.*

Debugging Example: Resistance Forge Weld

Modeled Physics & Numerics

- Elastoviscoplastic material model
- Electrical-thermal-mechanical coupling
- Curved contact interface
- Multiple constraints (some nodes in symmetry plane also in contact)
- Material softening due to heating
- Contact interactions transitioning from frictional to glued



Debugging Example: Resistance Forge Weld

Issue: run crashes

1. Explore the log file:
   - Error caught in material model
   - Multiple time step cutback attempts due to inverted elements before crash
   - No issue with electrical-thermal
2. Visualize results
   - Last converged solution looks wrong
   - Finding first occurrence of time step cutbacks can point you to the first accepted bad result
3. Attempted fixes:
   - Increase max iterations of model problem (no noticeable improvement).
   - Tighten contact solver tolerance(no noticeable improvement).
   - Ungroup interactions (big improvement)

```
Transfer Aria_To_Adagio, time 0.038, time step 0.001
Advance Adagio_Mechanical, time 0.038, time step 0.001
================================================================================================================
Begin load step =    46 Solution period time_weld is   0.0% complete
       Old Time        Time Step        New Time        Stop Time      CPU Time(s)     Wall Time(s)
     3.7000e-02       1.0000e-03      3.8000e-02      1.0000e+03       6.9063e+03       1.5030e+09
SIERRA execution failed during execute with the following exception:
Solve loadstep routine encountered a fatal error
Element ComputeInternalForce routine encountered a fatal error
Error: invalid strain rate (NaN).  Consider reducing time increment.
  error thrown from lame/include/models/Material.h:752
```

Possibly triggered by a bad solution on the previous step or sudden increase in time step? Code fails to recover from error and run crashes

```
Transfer Aria_To_Adagio, time 0.037, time step 7.629e-09
Advance Adagio_Mechanical, time 0.037, time step 7.629e-09
================================================================================================================
Begin load step =    45 Solution period time_weld is   0.0% complete
       Old Time        Time Step        New Time        Stop Time      CPU Time(s)     Wall Time(s)
     3.7000e-02       7.6294e-09      3.7000e-02      1.0000e+03       6.6741e+03       1.5030e+09
----------------------------------------------------------------------------------------------------------------
                          LINEAR       MP                      RELATIVE     BELYTSCH
                     RBM    ITER     ITER     RESIDUAL        RESIDUAL     REFERENCE        ENERGY DISPLACEMENT
----------------------------------------------------------------------------------------------------------------
                       -       -        0    1.484e+04      3.426e-01     4.330e+04                -            -
```

```
 Caught an Error:
Element ComputeInternalForce routine encountered a fatal error
In method:::: SelectiveDeviatoricElement::ComputeInternalForce :::::
The element on processor 1 with id 5483 has invalid Determinant(J): -2.84632e-09
   Attached nodes:  1107 1108 1767 1766 1162 1175 1731 1730
In method:::: SelectiveDeviatoricElement::ComputeInternalForce :::::
The element on processor 1 with id 5483 has invalid Determinant(J): -9.85255e-10
   Attached nodes:  1107 1108 1767 1766 1162 1175 1731 1730
In method:::: SelectiveDeviatoricElement::ComputeInternalForce :::::
The element on processor 1 with id 5484 has invalid Determinant(J): -4.54856e-09
   Attached nodes:  1108 1109 1768 1767 1175 1188 1732 1731
In method:::: SelectiveDeviatoricElement::ComputeInternalForce :::::
The element on processor 1 with id 5484 has invalid Determinant(J): -1.50281e-09
   Attached nodes:  1108 1109 1768 1767 1175 1188 1732 1731
In method:::: SelectiveDeviatoricElement::ComputeInternalForce :::::
The element on processor 1 with id 5488 has invalid Determinant(J): -2.13962e-10
   Attached nodes:  1766 1767 1772 1771 1730 1731 1736 1735
In method:::: SelectiveDeviatoricElement::ComputeInternalForce :::::
The element on processor 1 with id 5489 has invalid Determinant(J): -7.22179e-10
   Attached nodes:  1767 1768 1773 1772 1731 1732 1737 1736
Attempting to recover by cutting back time step
resetMaterialFailureMarks, Setting 0elements back to alive
Region adagio_mechanical will cut back time step
Transient Time_Weld failed, step 38, time 3.70000000e-02, time step 7.6294e-09
```

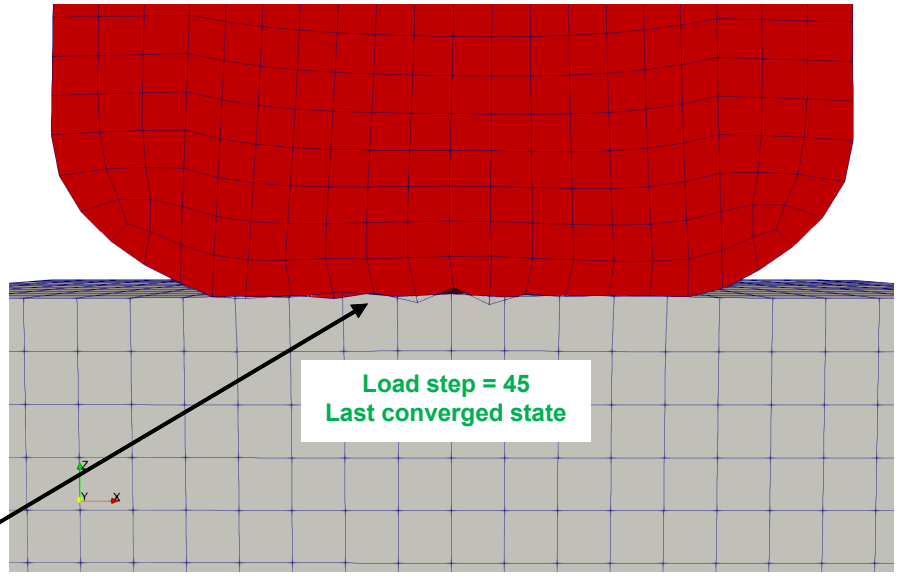
Time step cutbacks seen also early on in the simulation but code recovered. Time step too big?

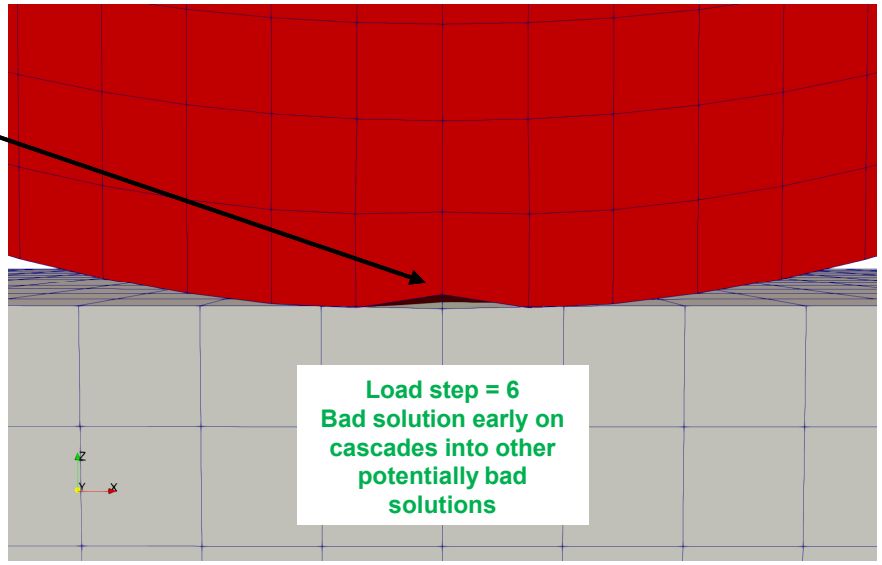
```
Performing contact search
Equation System aria_thermo_elec->main:
 * Step  : Transient, Strategy: NEWTON, Time: 3.80e-02, Step: 1.00e-03
 * Matrix: Solver: "aztec_solver", Unknowns: 13430, Nonzeros: unknown
 * Mesh  : Processor 0 of 4: 1707 of 5496 elems, 2315 of 6715 nodes
  N O N L I N E A R                L I N E A R
----------------------   -----------------------------------
Step  Resid    Delta     Itns Status  Resid    Asm/Slv Time
---- -------- --------   ---- ------ -------- ---------------
1    1.87e+08 3.29e+12   500   ok    1.12e+14 5.8e-02/4.5e-01
2    2.27e+17 5.67e+20   500   ok    3.44e+18 5.3e-02/4.6e-01
3    3.09e+21 2.49e+24   31    ok    2.80e+15 5.1e-02/5.6e-02
4    2.55e+21 2.49e+24   11    ok    1.41e+14 5.1e-02/4.0e-02
5    1.09e+10 3.67e+13   31    ok    4.39e+03 5.2e-02/5.6e-02
6    3.18e+07 3.26e+10   22    ok    1.11e+01 5.1e-02/4.9e-02
7    2.84e+02 2.93e+05   30    ok    2.38e-04 5.0e-02/5.8e-02
8    1.15e-01 3.24e+02   37    ok    4.91e-08 5.4e-02/6.6e-02
9    6.33e-04 5.15e+00   38    ok    4.07e-10 5.5e-02/6.5e-02
10   7.96e-08 4.09e-04   33    ok    8.03e-15 5.4e-02/6.2e-02
11   6.87e-14             NoOp          5.3e-02
Termination reason: 6.86502e-14 < nonlinear_residual_tolerance(1e-08),
                    and 0 < nonlinear_correction_tolerance(1e-06)
```

Debugging Example: Resistance Forge Weld

Issue: run crashes

1. Explore the log file:
   - Error caught in material model
   - Multiple time step cutback attempts due to inverted elements before crash
   - No issue with electrical-thermal
2. Visualize results
   - Last converged solution looks wrong
   - Finding first occurrence of time step cutbacks can point you to the first accepted bad result
3. Attempted fixes:
   - Increase max iterations of model problem (no noticeable improvement).
   - Tighten contact solver tolerance(no noticeable improvement).
   - Ungroup interactions (big improvement)





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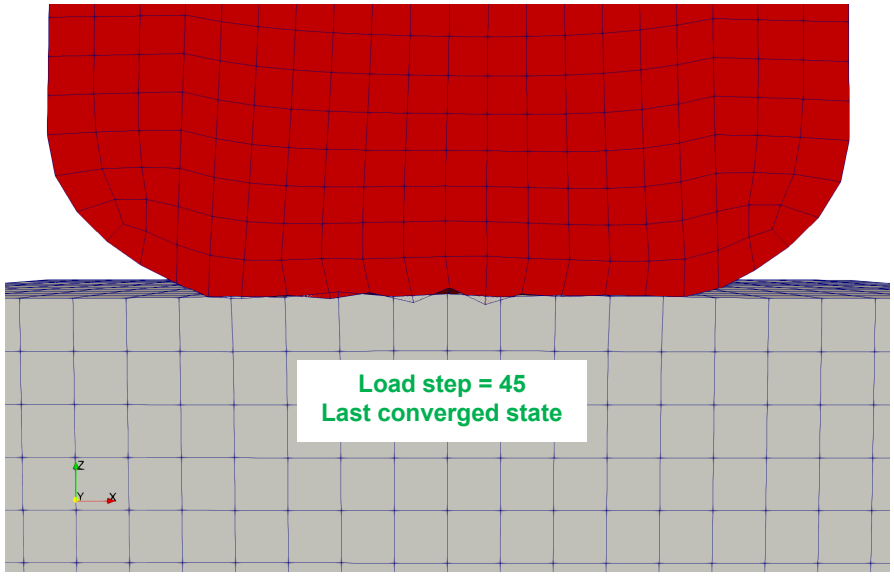

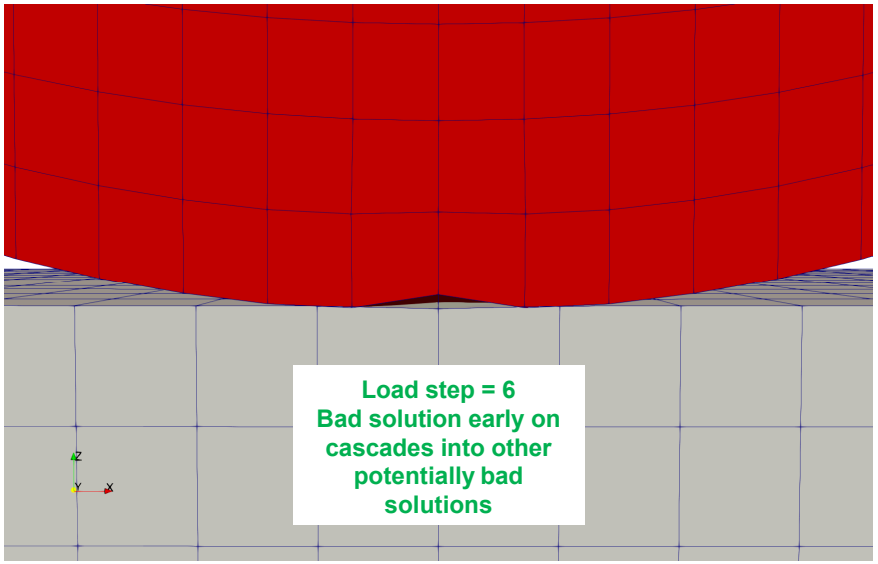

Debugging Example: Resistance Forge Weld

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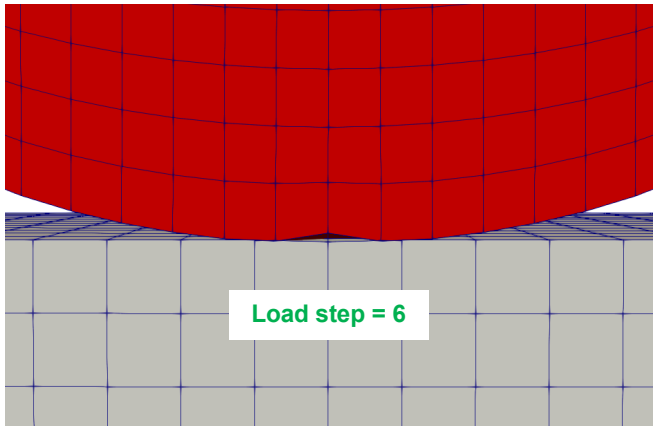
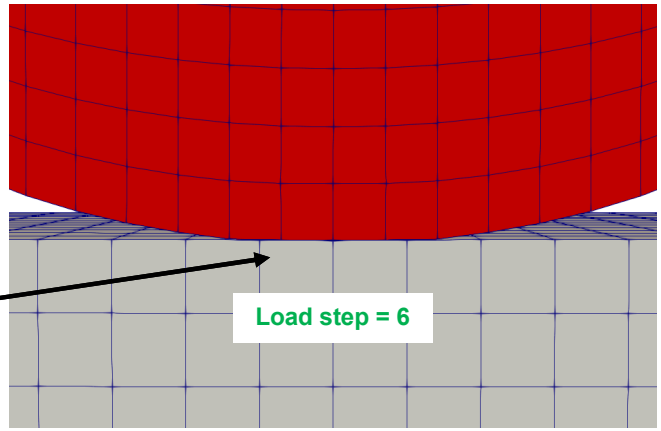



```
Begin Interaction mech_int1
  surfaces = block_1, block_2
  friction Model = nfd
  developer command: group interactions = false
End

begin nodal field dependent friction model nfd
  contact transition reduction method = min
  initial contact transition value = 0.1 # not bonded
End
```



Debugging Example: Resistance Forge Weld

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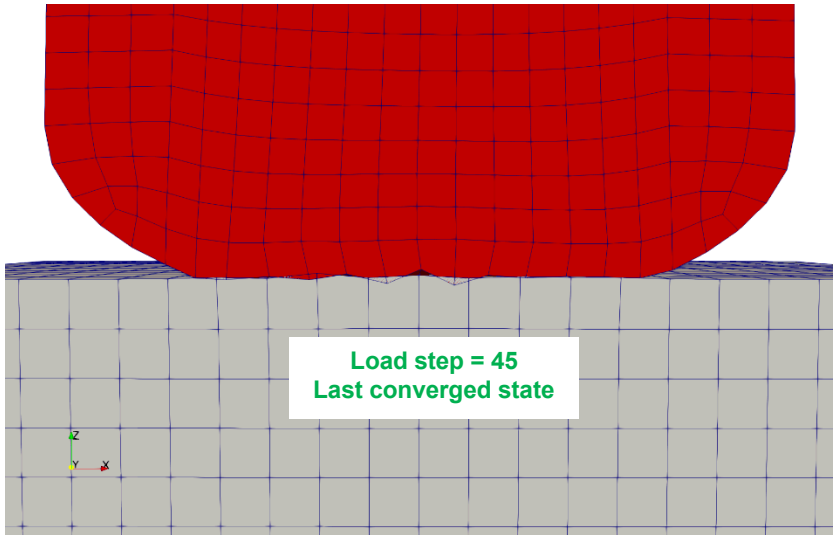

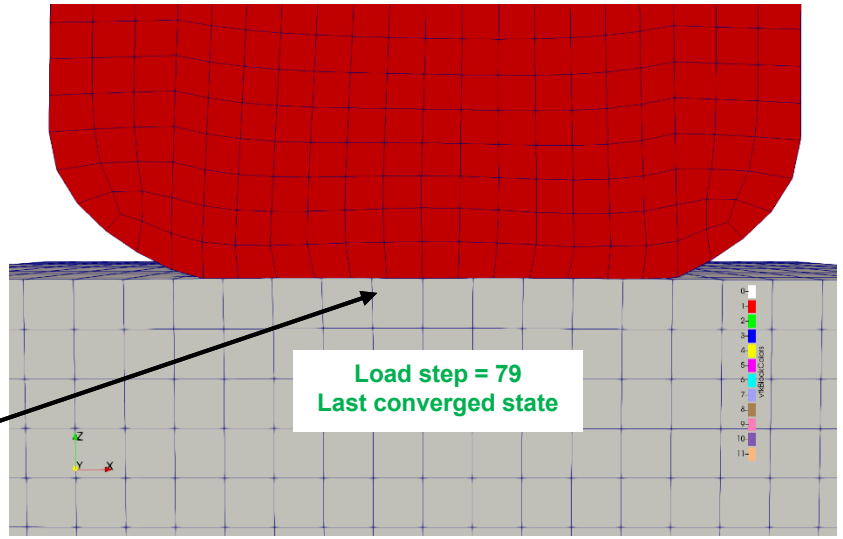

Debugging Example: Resistance Forge Weld

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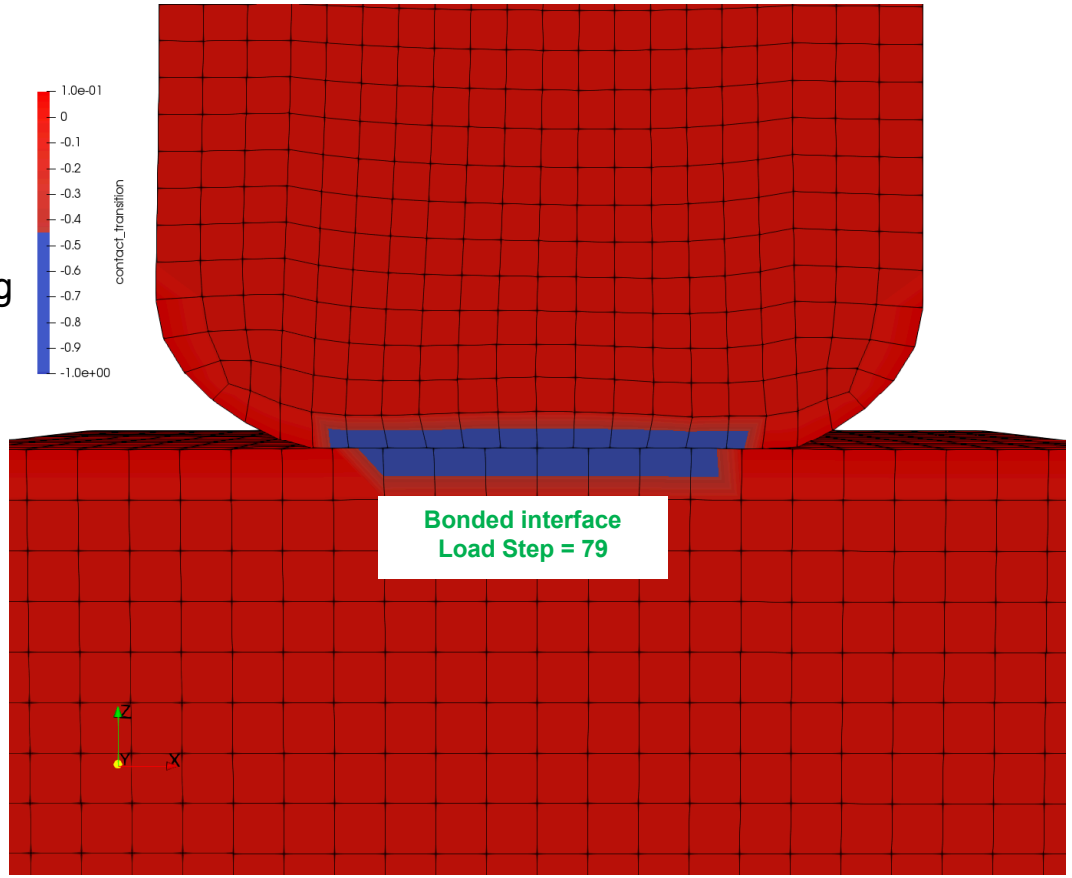
3. Attempted fixes:
   - Increase max iterations of model problem (no noticeable improvement).
   - Tighten contact solver tolerance(no noticeable improvement).
   - Ungroup interactions (big improvement)

- The option to ungroup interactions is still in development
- Our tests have not justified making it the default
- It improves the contact solution for some problems, such as this one with non-planar faces in contact.



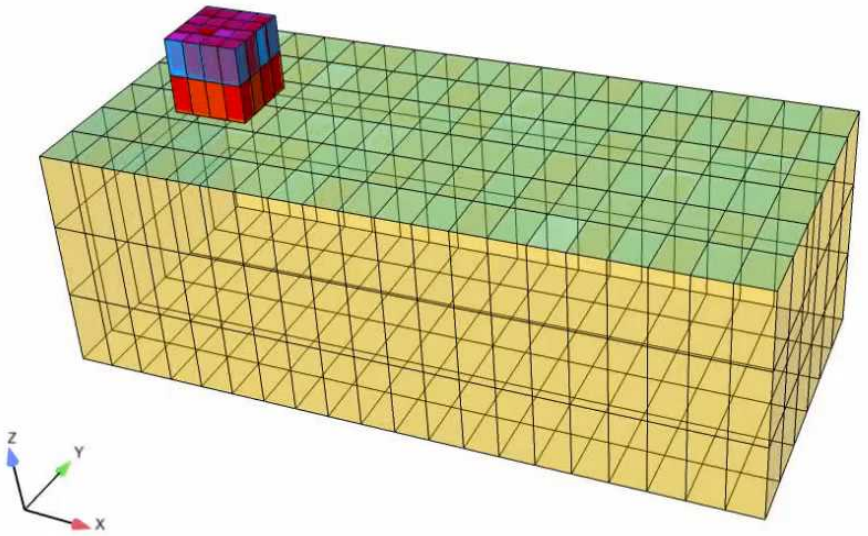
Debugging Example: Stiff Block on Soft Block

Sandia National Laboratories

Modeled Physics & Numerics

- Implicit quasi-statics
- Large difference in stiffness between contacting blocks
- Different mesh sizes between contacting blocks
- Large deformation contact
- Corner contact
- Stick-slip transition
- Mean-quadrature hex8
- Hyperelastic hourglass control

Initial setup:
contact lost & solver fails at 33% of simulation



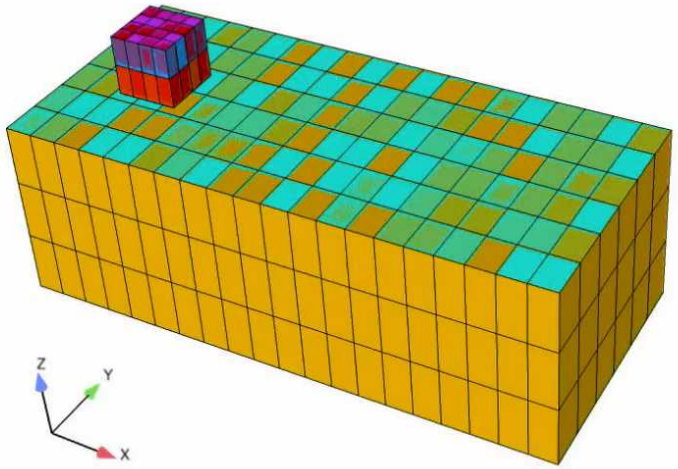
Debugging Example: Stiff Block on Soft Block

Sandia National Laboratories

Debugging Process

- Observed that corners of cube were penetrating the most
  - Changed from face_face to node_face for better corner contact
- Aided contact by manually defining most robust master/slave surfaces:
  - Coarse mesh → master
  - Fine mesh → slave
- Observed intermittent loss of contact_force of some nodes
  - Manually increased search tolerance

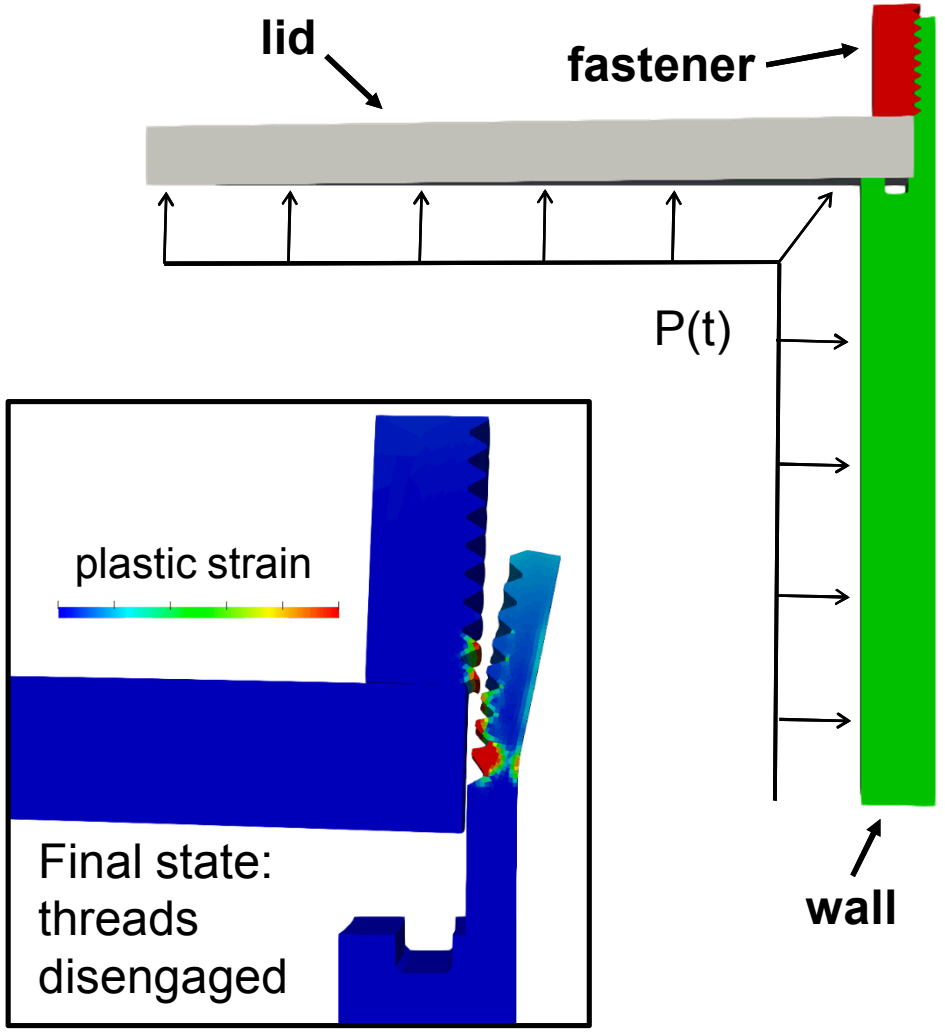
Final setup:
better contact enforcement & simulation runs to completion



Debugging Example: Pressurized Can

Modeled Physics & Numerics

- Mean-quadrature hex8
- Elasto-visco-plastic
- Thermal-mechanical
  - Temperature dependent material parameters
  - No thermal strain
- External heating above lid
- Ramped internal pressure
- Frictional contact
  - Between lid and wall of can
  - Along threaded fastener
- Contact seating
- Transition from static to dynamic
  - Lid/threads disengaging due to pressure and thermal softening
- Multiple stick-slip transitions



Debugging Example: Pressurized Can

Sandia National Laboratories

Input Deck Settings of a Successful & Efficient Analysis

```
begin implicit dynamics
  # switch from statics to dynamics
  # before lid starts disengaging
  active periods = p2
end

begin adaptive time stepping
  cutback factor = 0.5
  maximum failure cutbacks = 4
end adaptive time stepping

begin contact definition sliding
  skin all blocks = on
  begin friction model const_friction
    friction coefficient = 0.3
  end friction model const_friction
  begin interaction defaults
    general contact = on
    self contact = off
    friction model = const_friction
    al penalty = 0.005
  end interaction defaults
end contact definition sliding
```

```
begin solver
  begin loadstep predictor
    type = scale_factor
    scale factor = 0.0
  end loadstep predictor

  begin control contact
    target relative residual = 1.0e-4
    acceptable relative residual = 1.0e-3
    maximum iterations = 50
  end control contact

  begin cg
    target relative residual = 5.0e-5
    acceptable relative residual = 1.0e3
    maximum iterations = 30
    reference = belytschko
    begin full tangent preconditioner
      nodal preconditioner = probe
      minimum smoothing iterations = 5
      small number of iterations = 20
    end full tangent preconditioner
  end cg
end solver
```

Debugging Example: Pressurized Can

Sandia National Laboratories

Input Deck Settings of a Successful & Efficient Analysis

```
begin implicit dynamics
  # switch from statics to dynamics
  # before lid starts disengaging
  active periods = p2
end

begin adaptive time stepping
  cutback facto
  maximum failu
end adaptive ti

begin contact d
  skin all bloc
  begin friction model const_friction
    friction coefficient = 0.3
  end friction model const_friction
  begin interaction defaults
    general contact = on
    self contact = off
    friction model = const_friction
    al penalty = 0.005
  end interaction defaults
end contact definition sliding
```

In the following slides we explore what happens if these settings are used but with one command modified.

```
begin solver
  begin loadstep predictor
    type = scale_factor
    scale factor = 0.0
  end loadstep predictor

  begin control contact
                                    = 1.0e-4
                                   al = 1.0e-3

    target relative residual = 5.0e-5
    acceptable relative residual = 1.0e3
    maximum iterations = 30
    reference = belytschko
    begin full tangent preconditioner
      nodal preconditioner = probe
      minimum smoothing iterations = 5
      small number of iterations = 20
    end full tangent preconditioner
  end cg
end solver
```

Debugging Example: Pressurized Can

Sandia National Laboratories

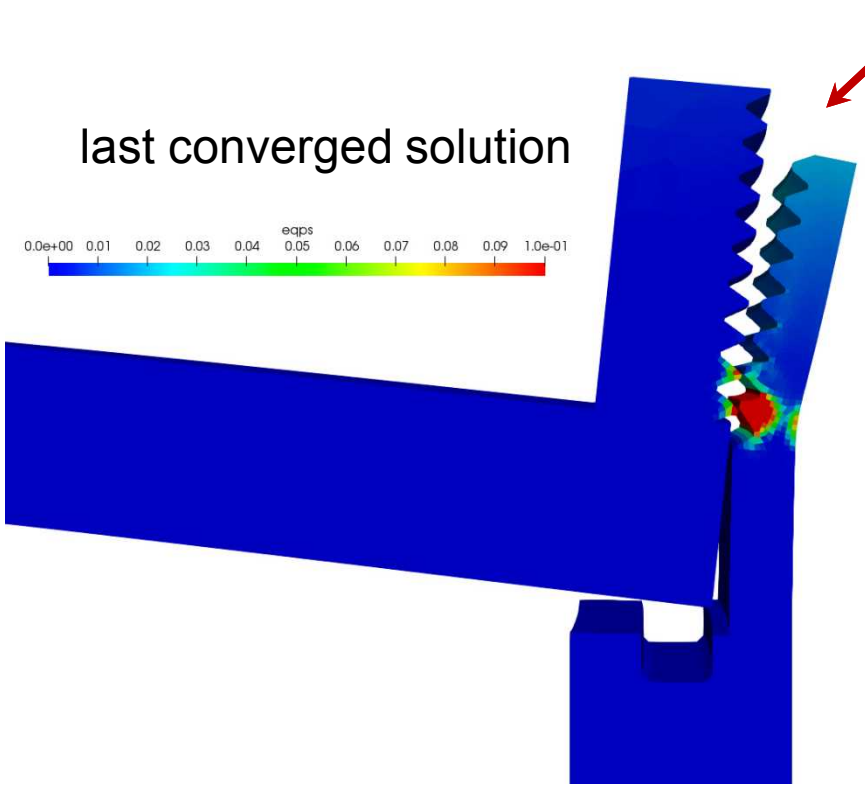
Implicit Dynamics vs. Quasi-statics When Threads Disengage

```
begin implicit dynamics
  active periods = p2
end
```

```
# begin implicit dynamics
#   active periods = p2
# end
```

runs to completion

fails: immediately before threads disengaging



Debugging Example: Pressurized Can

Non-default AL Penalty vs. Default

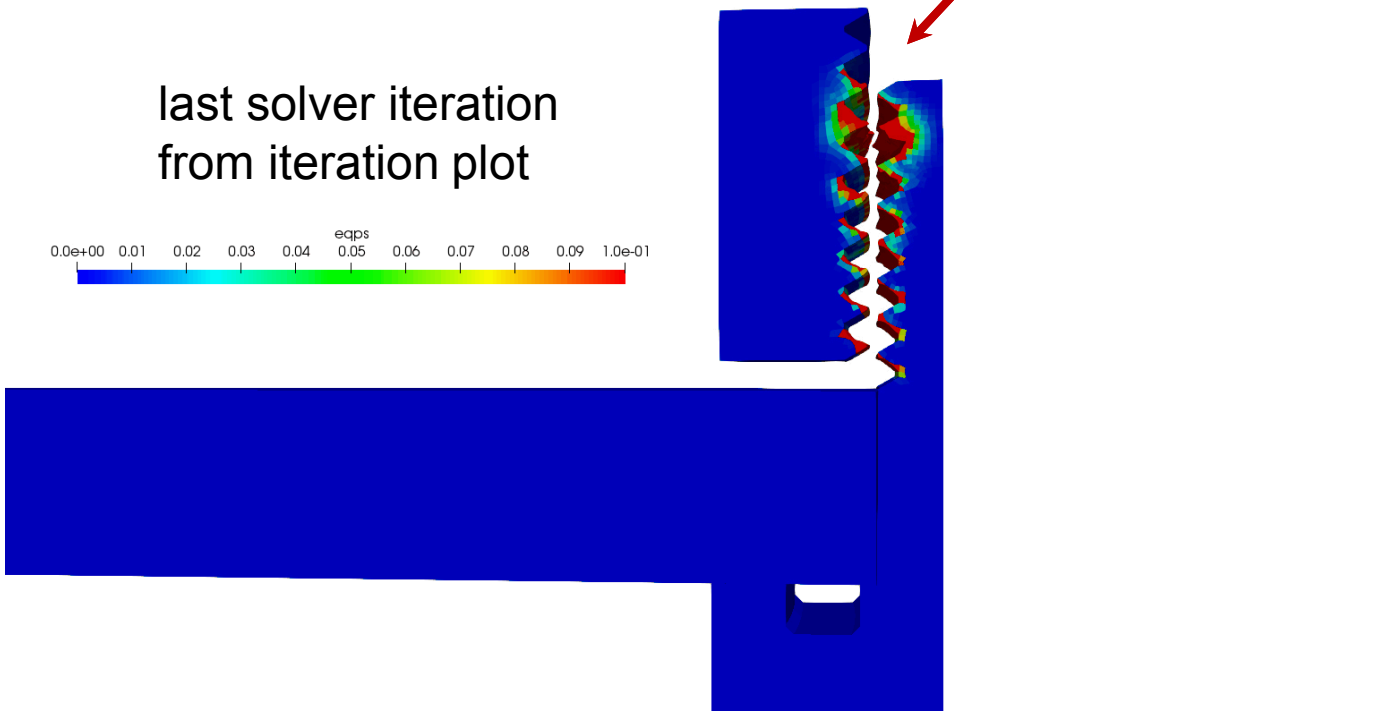
```
begin interaction defaults
  …
  al penalty = 0.005
end interaction defaults
```

runs to completion

```
begin interaction defaults
  …
  # default [al penalty = 1.0]
end interaction defaults
```

fails: contact seating unsuccessful in first step

last solver iteration
from iteration plot



Debugging Example: Pressurized Can

Skin All Blocks w/ General Contact vs. Specifying Surface-Surface Interactions

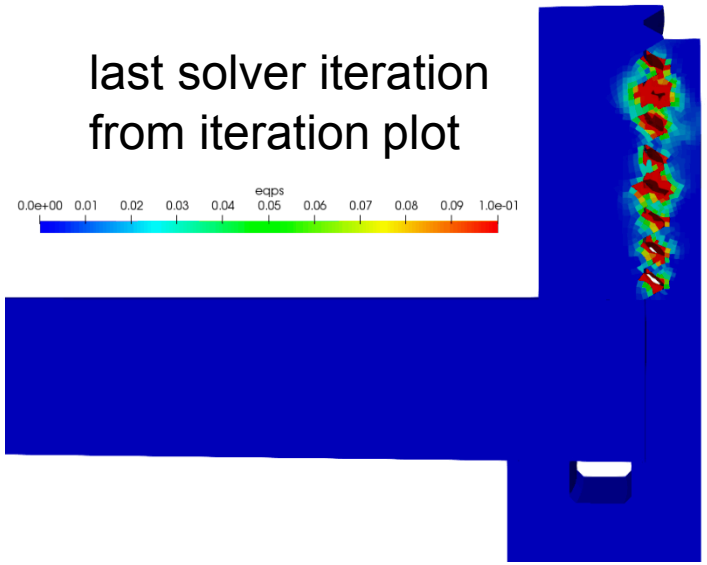
```
begin contact definition sliding
  skin all blocks = on
  begin interaction defaults
    general contact = on
    ...
```

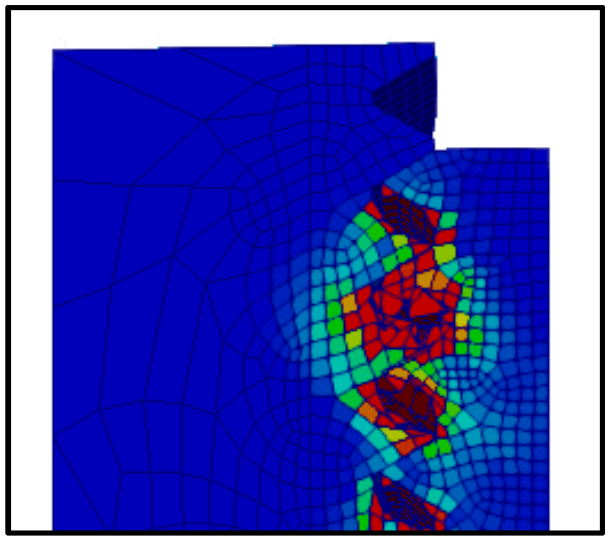
runs to completion

```
contact surface cs5 contains surface_5
contact surface cs6 contains surface_6
begin interaction threads
  master = surf_5
  slave = surf_6
  friction model = const_friction
end interaction threads
... [ring-lid and lid-wall interactions]
```

fails: inverted elements in first step

last solver iteration
from iteration plot





Debugging Example: Pressurized Can

Not Using Predictor vs. Using Predictor

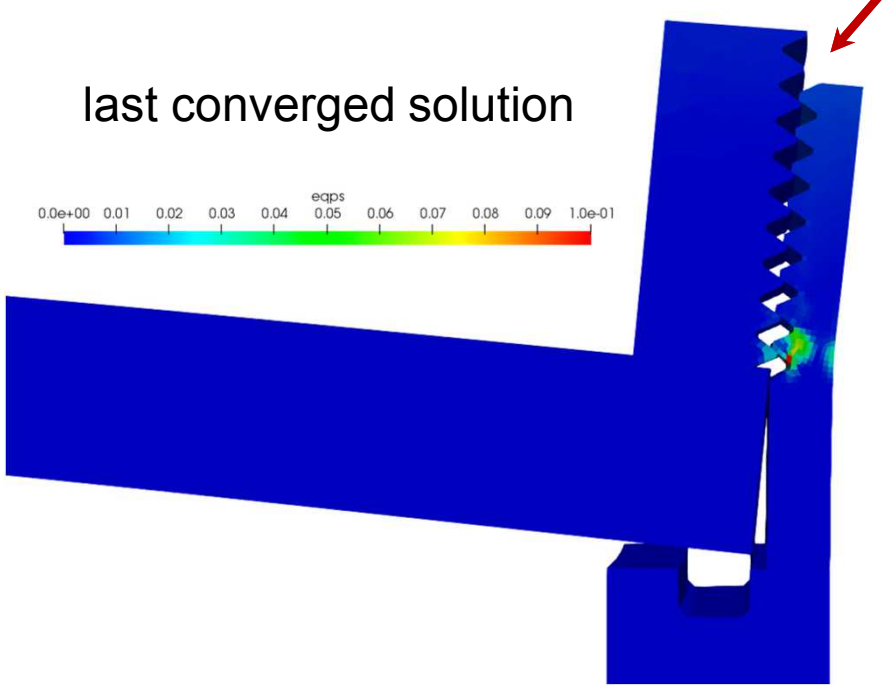
```
begin loadstep predictor
  type = scale_factor
  scale factor = 0.0
end loadstep predictor
```

runs to completion

```
begin loadstep predictor
  type = scale_factor
  scale factor = 1.0
end loadstep predictor
```

fails: 2 steps before threads disengage

last converged solution



Debugging Example: Pressurized Can

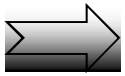
Sandia National Laboratories

Using Smoothing Iterations vs. Not Using Smoothing Iterations

```
begin cg
  ...
  begin full tangent preconditioner
    ...
    minimum smoothing iterations = 5
  end full tangent preconditioner
end cg
```

runs to completion

run time = 1300 sec.



```
begin cg
  ...
  begin full tangent preconditioner
    ...
    # default [minimum smoothing iterations = 0]
  end full tangent preconditioner
end cg
```

runs to completion

run time = 5000 sec.

~4X slowdown

Debugging Example: Pressurized Can

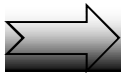
Sandia National Laboratories

Using Small Number of Iterations vs. Not Using Small Number of Iterations

```
begin cg
  ...
  begin full tangent preconditioner
    ...
    small number of iterations = 20
  end full tangent preconditioner
end cg
```

runs to completion

run time = 1300 sec.



```
begin cg
  ...
  begin full tangent preconditioner
    ...
    # default [update tangent every step]
  end full tangent preconditioner
end cg
```

runs to completion

run time = 2700 sec.

~2X slowdown

Summary

Sandia National Laboratories

- One set of contact solver settings will not be robust for all problems.
- Use the recommended settings to start and be careful when moving parameters from one analysis to the next.
- Identify potential pitfalls in your model.
- The log file is your first line of defense.
- Refer to the “Implicit Solver” and “Contact” sections in the Sierra/SM User’s Guide for further guidance, as well as the “Troubleshooting Guide for Implicit Convergence” appendix.
- Reach out to sierra-help, other analysts or a developer near you.
- Analyst input is of paramount importance to improve default solver settings and log file readability.