Practical Approaches to Formally Verify Concurrent Software

Ganesh Gopalakrishnan

Microsoft HPC Institutes,
NSF CNS-0509379
SRC Contract TJ 1318

http://www.cs.utah.edu/formal_verification

(talk is kept at above URL under presentations/ce-junior-seminar-2008.pptx)
Multicores are the future!

Why?

(photo courtesy of Intel Corporation.)
Multicores are the future!

Why?

- That is the only way to get more compute power
- Energy per compute operation lowered thru the use of parallelism
  - e.g. Today’s DSP processors

(photo courtesy of Intel Corporation.)
How many different types of multicore CPUs?

- Quite a variety
- Use in cloud computing
- Use in hand-helds
- Use in embedded devices
- Use in Graphics / Gaming
- Use in HPC
- ...

- A plethora of SW and HW challenges

(photo courtesy of Intel Corporation.)
Multicore Challenges:
Need to employ / teach concurrent programming at an unprecedented scale!

Some of today’s proposals:
- Threads (various)
- Message Passing (various)
- Transactional Memory (various)
- OpenMP
- MPI
- Intel’s Ct
- Microsoft’s Parallel Fx
- Cilk Arts’s Cilk
- Intel’s TBB
- Nvidia’s Cuda
- ...

(photo courtesy of Intel Corporation.)
Multicore Challenges:
What about HARDWARE VERIFICATION?

Some of today’s successes:

* Execution unit verification can be done using Formal Methods!
  
  Latest Example: The entire Nehalem execution unit has been formally verified using Symbolic Trajectory Evaluation (within the power of the STE method, of course, but still exhaustive for MANY aspects)

* Control unit verification remains a huge challenge; but even here, verification of controller MODELS is being done formally...

(photo courtesy of Intel Corporation.)
Sequential program verification remains hard!

```c
main(){ int Z1, Z2, Z3;
    int x1, x2;
    int z11, z12, z13, z21, z22, z23;
    /* x1 = x2; */
    z11 = z21; z12 = z22; z13 = z23;

    if (x1 == 1) z11 = \[Z1\]; if (x1 == 2) z12 = \[Z2\]; if (x1 == 3) z13 = \[Z3\];

    if (x2 == 1) z21 = \[Z1\]; else if (x2 == 2) z22 = \[Z2\]; else if (x2 == 3) z23 = \[Z3\];

    assert((z11 + z12 + z13) == (z21 + z22 + z23)); }
```

How might we prove / disprove the assertion for ALL possible initial values of the variables?

Welcome to symbolic verification – a Formal Verification Method (STE is very similar to this style of reasoning...)
HW Control Verification Challenges (e.g.)
Cache Coherence Protocols are becoming VERY complex.
No industry builds a microprocessor without formally verifying them at a high level (conceptual level) of “guard / action” rules...

State Space grows multiplicatively across the hierarchy!
Verification will become harder
HW implementations of cache coherence protocols exhibit fine-grained concurrency — again formal methods are enjoying growing successes (but a lot remains to be done).
Other issues in HW verification: growing analog behavior of “digital components”
Back to our main topic – CONCURRENCY!

Concurrency verification is harder!!

main(){
    int Z1, Z2, Z3;
    int x1, x2;
    int z11, z12, z13, z21, z22, z23;
    /* x1 = x2; */
    z11 = z21; z12 = z22; z13 = z23;

    if (x1 == 1) z11 = Z1; if (x1 == 2) z12 = Z2; if (x1 == 3) z13 = Z3;
    if (x2 == 1) z21 = Z1; else if (x2 == 2) z22 = Z2; else if (x2 == 3) z23 = Z3;
    assert((z11 + z12 + z13) == (z21 + z22 + z23)); }

(* More specifically: at each “grain boundary” of atomicity lurks a potential interleaving that was not considered...*)
Q: Why is concurrent program debugging hard?
A: Too many interleavings!!

• Suppose only the interleavings of the red cards matter
• Then don’t try all riffle-shuffles \((12!) \div ((6!) \cdot (6!)) = 924\)
• Instead just try TWO shuffles of the decks  !!
The Growth of $(n.p)! / (n!)^p$

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>....</th>
<th>Thread p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>1:</td>
<td></td>
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<tr>
<td>2:</td>
<td>2:</td>
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<td>3:</td>
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<tr>
<td>4:</td>
<td>4:</td>
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<tr>
<td>...</td>
<td>...</td>
<td></td>
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<tr>
<td>n:</td>
<td>n:</td>
<td></td>
</tr>
</tbody>
</table>

- Unity / Murphi “guard / action” rules: $n=1$, $p=R$  \( R! \) interleavings
- $p = 3$, $n = 5$  \( \Rightarrow \)  \( 10^6 \) interleavings
- $p = 3$, $n = 6$  \( \Rightarrow \)  \( 17 * 10^6 \) interleavings
- $p = 4$, $n = 5$  \( \Rightarrow \)  \( 10^{10} \) interleavings
Ad-hoc Testing is INEFFECTIVE for thread verification!

Thread 1  ....  Thread p

1:  
2:  
3:  
4:  
...  
n:  

1:  
2:  
3:  
4:  
...  
n:  

• MUST reduce the number of interleavings considered

• Rigorous proof to back omitting interleavings

• DYNAMIC PARTIAL ORDER REDUCTION achieves both
Example: Dining Philosophers in C / PThreads...

```c
#include <stdlib.h>     // Dining Philosophers with no deadlock
#include <pthread.h>    // all phils but "odd" one pickup their
#include <stdio.h>      // left fork first; odd phil picks
#include <string.h>     // up right fork first
#include <malloc.h>
#include <errno.h>
#include <sys/types.h>
#include <assert.h>

#define NUM_THREADS 3

pthread_mutex_t mutexes[NUM_THREADS];
pthread_cond_t conditionVars[NUM_THREADS];
int permits[NUM_THREADS];
pthread_t tids[NUM_THREADS];

int data = 0;

void * Philosopher(void * arg){
    int i;
    i = (int)arg;

    // pickup left fork
    pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
    while (permits[i%NUM_THREADS] == 0) {
        printf("P%d : tryget F%d
", i, i%NUM_THREADS);
        pthread_cond_wait(&conditionVars[i%NUM_THREADS],&mutexes[i%NUM_THREADS]);
        permits[i%NUM_THREADS] = 0;
        printf("P%d : get F%d\n", i, i%NUM_THREADS);
        pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);
    }

    // pickup right fork
    pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
    while (permits[(i+1)%NUM_THREADS] == 0) {
        printf("P%d : tryget F%d\n", i, (i+1)%NUM_THREADS);
        pthread_cond_wait(&conditionVars[(i+1)%NUM_THREADS],&mutexes[(i+1)%NUM_THREADS]);
        permits[(i+1)%NUM_THREADS] = 0;
        printf("P%d : get F%d\n", i, (i+1)%NUM_THREADS);
        pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
    }

    printf("philosopher %d thinks \n",i);
    printf("%d\n", i);

    // data = 10 * data + i;
    fflush(stdout);

    // putdown right fork
    pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
    permits[(i+1)%NUM_THREADS] = 1;
    printf("P%d : put F%d\n", i, (i+1)%NUM_THREADS);
    pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
    pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
}
```
Philosophers in PThreads

// putdown left fork
pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
permits[i%NUM_THREADS] = 1;
printf("P%d : put F%d \n", i, i%NUM_THREADS);
pthread_cond_signal(&conditionVars[i%NUM_THREADS]);
pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);

// putdown right fork
pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
permits[(i+1)%NUM_THREADS] = 1;
printf("P%d : put F%d \n", i, (i+1)%NUM_THREADS);
pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);

return NULL;
}

int main(){
    int i;

    for (i = 0; i < NUM_THREADS; i++)
        pthread_mutex_init(&mutexes[i], NULL);
    for (i = 0; i < NUM_THREADS; i++)
        pthread_cond_init(&conditionVars[i], NULL);
    for (i = 0; i < NUM_THREADS; i++)
        permits[i] = 1;

    for (i = 0; i < NUM_THREADS - 1; i++)
        pthread_create(&tids[i], NULL,
            OddPhilosopher, (void*)(NUM_THREADS - 1) );

    for (i = 0; i < NUM_THREADS; i++){
        pthread_join(tids[i], NULL);
    }

    for (i = 0; i < NUM_THREADS; i++)
        pthread_mutex_destroy(&mutexes[i]);
    for (i = 0; i < NUM_THREADS; i++)
        pthread_cond_destroy(&conditionVars[i]);

    //printf(" data = %d \n", data);
    //assert( data != 201);
    return 0;
}
‘Plain run’ of Philosophers

gcc -g -O3 -o nobug examples/Dining3.c -L ./lib -lpthread -lstdc++ -lssl

% time nobug

P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P1 : put F2
P1 : put F1
P2 : get F0
P2 : get F2
2
P2 : put F2
P2 : put F0

real   0m0.075s
user   0m0.001s
sys    0m0.008s
Buggy Philosophers in PThreads

// putdown left fork
pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
permits[i%NUM_THREADS] = 1;
printf("P%d : put F%d \n", i, i%NUM_THREADS);
pthread_cond_signal(&conditionVars[i%NUM_THREADS]);
pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);

// putdown right fork
pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
permits[(i+1)%NUM_THREADS] = 1;
printf("P%d : put F%d \n", i, (i+1)%NUM_THREADS);
pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
return NULL;

int main(){
    int i;
    for (i = 0; i < NUM_THREADS; i++)
        pthread_mutex_init(&mutexes[i], NULL);
    for (i = 0; i < NUM_THREADS; i++)
        pthread_cond_init(&conditionVars[i], NULL);
    for (i = 0; i < NUM_THREADS; i++)
        permits[i] = 1;
    for (i = 0; i < NUM_THREADS-1; i++){
        pthread_create(&tids[i], NULL, Philosopher, (void*)(i) );
    }

    pthread_create(&tids[NUM_THREADS-1], NULL,
                   Philosopher, (void*)(NUM_THREADS-1) );

    for (i = 0; i < NUM_THREADS; i++){
        pthread_join(tids[i], NULL);
    }

    for (i = 0; i < NUM_THREADS; i++)
        pthread_mutex_destroy(&mutexes[i]);
    for (i = 0; i < NUM_THREADS; i++)
        pthread_cond_destroy(&conditionVars[i]);

    printf(" data = %d \n", data);
    assert( data != 201);
    return 0;
}
'Plain run' of buggy philosopher .. bugs missed by testing

gcc -g -O3 -o buggy examples/Dining3Buggy.c -L ./lib -lpthread -lstdc++ -lssl

% time buggy

P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P1 : put F2
P1 : put F1
P2 : get F2
P2 : get F0
2
P2 : put F0
P2 : put F2

real 0m0.084s
user 0m0.002s
sys 0m0.011s
```c
#include <stdlib.h>     // Dining Philosophers with no deadlock
#include <pthread.h>    // all phils but "odd" one pickup their
#include <stdio.h>      // left fork first; odd phil picks
#include <string.h>     // up right fork first
#include <malloc.h>
#include <errno.h>
#include <sys/types.h>
#include <assert.h>

#define NUM_THREADS 3

pthread_mutex_t mutexes[NUM_THREADS];
pthread_cond_t conditionVars[NUM_THREADS];
int permits[NUM_THREADS];
pthread_t tids[NUM_THREADS];

int data = 0;

void * Philosopher(void * arg){
    int i;
    i = (int)arg;

    // pickup left fork
    pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
    while (permits[i%NUM_THREADS] == 0) {
        printf("P%d : tryget F%d\n", i, i%NUM_THREADS);
        pthread_cond_wait(&conditionVars[i%NUM_THREADS],&mutexes[i%NUM_THREADS]);
    }
    permits[i%NUM_THREADS] = 0;
    printf("P%d : get F%d\n", i, i%NUM_THREADS);
    pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);

    // pickup right fork
    pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
    while (permits[(i+1)%NUM_THREADS] == 0) {
        printf("P%d : tryget F%d\n", i, (i+1)%NUM_THREADS);
        pthread_cond_wait(&conditionVars[(i+1)%NUM_THREADS],&mutexes[(i+1)%NUM_THREADS]);
    }
    permits[(i+1)%NUM_THREADS] = 0;
    printf("P%d : get F%d\n", i, (i+1)%NUM_THREADS);
    pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
    //printf("philosopher %d thinks \n",i);
    printf("%d\n", i);

    // data = 10 * data + i;
    fflush(stdout);

    // putdown right fork
    pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
    permits[(i+1)%NUM_THREADS] = 1;
    printf("P%d : put F%d\n", i, (i+1)%NUM_THREADS);
    pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
    pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
}
```

‘Plain runs’ of buggy philosopher – bug still very dodgy ...

gcc -g -O3 -o
buggysleep examples/Dining3BuggyNanosleep0.c
   -L ./lib -lpthread -lstdc++ -lssl

% buggysleep

P0 : get F0
P0 : sleeping 0 ns
P1 : get F1
P1 : sleeping 0 ns
P2 : get F2
P2 : sleeping 0 ns
P0 : tryget F1
P2 : tryget F0
P1 : tryget F2

First run deadlocked – second did not ..
Dijkstra’s famous quote

- Testing only confirms the presence of errors... never its absence

- MUCH MORE TRUE for concurrent software
Some terminology and an overview

• Concurrent includes Parallel (aka shared memory) and Distributed (aka message passing)

• In our research group, we have developed tools to verify PRACTICAL Parallel and Distributed software

• Currently for Pthreads (parallel) and MPI (distributed)

• This talk mainly focusses on Parallel (Pthreads / C) software verification
An important use of message passing

The scientific community is increasingly employing expensive supercomputers that employ distributed programming libraries….

(BlueGene/L - Image courtesy of IBM / LLNL)

...to program large-scale simulations in all walks of science, engineering, math, economics, etc.

(Image courtesy of Steve Parker, CSAFE, Utah)
Verification Realities

Code written using mature libraries (MPI, OpenMP, PThreads, ...)

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Verification Realities

- Code written using mature libraries (MPI, OpenMP, PThreads, ...)
- API calls made from real programming languages (C, Fortran, C++)
Verification Realities

- Code written using mature libraries (MPI, OpenMP, PThreads, ...)
- API calls made from real programming languages (C, Fortran, C++)
- Runtime semantics determined by realistic Compilers and Runtimes
Verification Realities

- Code written using mature libraries (MPI, OpenMP, PThreads, ...)
- API calls made from real programming languages (C, Fortran, C++)
- Runtime semantics determined by realistic Compilers and Runtimes

How best to verify codes that will run on actual platforms?
Workflow of Parallel Software Verification tool “Inspect”

- Multithreaded C/C++ program
- Instrumentation
- Instrumented program
- Thread library wrapper
- Compile
- Executable
- Thread 1
- Thread n
- Scheduler
- Request/permit
void * Philosopher(void * arg){
    int i;
    i = (int)arg;
...
    pthread_mutex_lock(&mutexes[i%3]);
...
    while (permits[i%3] == 0) {
        printf("P%d : tryget F%d\n", i, i%3);
        pthread_cond_wait(...);
    }
...
    permits[i%3] = 0;
...
    pthread_cond_signal(&conditionVars[i%3]);
    pthread_mutex_unlock(&mutexes[i%3]);
    return NULL;
}
Inspect of nonbuggy and buggy Philosophers ..

```
./instrument file.c
./compile file.instr.c
./inspect ./target

P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : get F0
P0 : get F1
0
P1 : tryget F1 <<

Total number of runs: 48,
Transitions explored: 1814
Used time (seconds): 7.999327
```

```
=== run 2 ===
P0 : get F0
P0 : get F1
0
P0 : put F0
P0 : get F1
1
P1 : put F1
P1 : put F0
P2 : get F2
P2 : get F0
P2 : put F0
P2 : put F2
2

=== run 28 ===
P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P2 : tryget F2
P2 : put F2
P2 : tryget F0
Found a deadlock!!
(0, thread_start)
(0, obj_write, 2)
(0, obj_write, 3)
(0, mutex_init, 5)
(0, mutex_init, 6)
(0, mutex_init, 7)
(0, cond_init, 8)
(0, cond_init, 9)
(0, cond_init, 10)
(1, mutex_lock, 5)
(1, mutex_lock, 6)
(1, mutex_lock, 7)
(1, obj_read, 2)
(1, obj_write, 3)
(2, mutex_lock, 6)
(2, obj_read, 3)
```

```
num of threads = 1
```

```
=== run 1 ===
P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P2 : get F0
P2 : get F2
2
P2 : put F2
P2 : put F2

=== run 2 ===
P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P2 : tryget F2
P2 : put F2
P2 : put F0
P1 : put F1

Total number of runs: 29,
killed-in-the-middle runs: 4
Transitions explored: 1193
Used time (seconds): 5.990523
```
The Growth of $(n.p)! / (n!)^p$ for Dining$p$.c illustrating the MAIN technology behind Inspect

- Dining$p$.c has $n = 4$ (roughly)

- $p = 3$: We get $34,650$ (loose upper-bound) versus $48$ with DPOR

- $p = 5$: We get $305,540,235,000$ versus $2,375$ with DPOR

- DPOR really works well in reducing the number of interleavings !!

- Testing will have to exhibit its cleverness among $3 \times 10^{11}$ interleavings
Dynamic Partial Order Reduction (DPOR)
“animatronics”

lock(y)  lock(x)  lock(x)

.............  .............  .............

unlock(y)  unlock(x)  unlock(x)
An Overview of ISP

ISP looks ONLY for “low-hanging” bugs

Three bug classes it looks for are presented next
Deadlock pattern...
Communication Race Pattern...

OK

P0
---
r(*);
---
r(P1);

P1
---
s(P0);

P2
---
s(P0);

NOK

P0
---
r(*);
---
r(P1);

P1
---
s(P0);

P2
---
s(P0);
Resource Leak Pattern...

P0
---
some_allocation_op(&handle);

FORGOTTEN DEALLOC  !!
Why is even this much debugging hard?

The “crooked barrier” quiz will show you why...

```
P0
---
MPI_Isend ( P2 )
MPI_BARRIER

P1
---
MPI_BARRIER
MPI_Isend ( P2 )

P2
---
MPI_BARRIER
MPI_Irecv ( ANY )

Will P1’s Send Match P2’s Receive?
```
It will! Here is the animation
MPI Behavior

The “crooked barrier” quiz

P0
---
MPI_Isend ( P2 )
MPI_Barrier

P1
---
MPI_Barrier
MPI_Isend( P2 )

P2
---
MPI_Irecv ( ANY )
MPI_Barrier
MPI Behavior

The “crooked barrier” quiz

- P0
  - MPI_Isend ( P2 )
  - MPI_Barrier

- P1
  - MPI_Barrier
  - MPI_Isend( P2 )

- P2
  - MPI_Irecv ( ANY )
  - MPI_Barrier
The “crooked barrier” quiz

MPI Behavior
The “crooked barrier” quiz

MPI Behavior

The diagram illustrates the sequence of operations involving processes P0, P1, and P2. The operations include:

- **MPI_Isend(P2)** on P0
- **MPI_Barrier** on P0
- **MPI_Isend(P2)** on P1
- **MPI_Barrier** on P1
- **MPI_Irecv(ANY)** on P2
- **MPI_Barrier** on P2
MPI Behavior

The “crooked barrier” quiz
We need a dynamic verification approach to be aware of the details of the API behavior...
Reason why DPOR won’t do: Can’t replay with P1’s send coming first!!

See our CAV 2008 paper for details (also EuroPVM / MPI 2008)
Workflow of ISP

- Manifest only/all relevant interleavings (DPOR)
- Manifest ALL relevant interleavings of the MPI Progress Engine:
  - Done by DYNAMIC REWRITING of WILDCARD Receives.
The basic PMPI trick played by ISP
Using PMPI

User Function

MPI_Send

PMPI_Send

SendEnvelope

MPI_Send

In MPI Runtime

TCP socket

PO’s Call Stack

PO: MPI_Send

Scheduler

MPI Runtime
Main idea behind POE

• MPI has a pretty interesting out-of-order execution semantics
  – We “gleaned” the semantics by studying the MPI reference document, talking to MPI experts, reading the MPICH2 code base, AND using our formal semantics

• “Give MPI its own dose of medicine”
  – I.e. exploit the OOO semantics
  – Delay sending weakly ordered operations into the MPI runtime
  – Run a process, COLLECT its operations, DO NOT send it into the MPI runtime
  – SEND ONLY WHEN ABSOLUTELY POSITIVELY forced to send an action
  – This is the FENCE POINT within each process

• This way we are guaranteed to discover the maximal set of sends that can match a wildcard receive !!!
The POE algorithm

POE = Partial Order reduction avoiding Elusive Interleavings
POE

P0

Isend(1, req)

Barrier

Wait(req)

P1

Irecv(*, req)

Barrier

Recv(2)

Wait(req)

P2

Isend(1, req)

Barrier

Isend(1)

Barrier

MPI Runtime

Scheduler
POE

MPI Runtime

Scheduler

Isend(1)
Barrier

Irecv(*)
Barrier

P0

Isend(1, req)

Barrier

Wait(req)

P1

Irecv(*, req)

Barrier

P2

Isend(1, req)

Barrier

Recv(2)

Wait(req)

Wait(req)
POE

MPI Runtime

Scheduler

Irecv(*)

Barriers

Irecv(*, req)

Isend(1, req)

Irecv(*)

Barrier

Irecv(*)

Isend(1)

Barrier

Barrier

Barrier
Once ISP discovers the maximal set of sends that can match a wildcard receive, it employs DYNAMIC REWRITING of wildcard receives into SPECIFIC RECEIVES !!
Obtaining and Running Inspect and ISP

- From [http://www.cs.utah.edu/formal_verification](http://www.cs.utah.edu/formal_verification)
- But get it from the authors for the latest versions (ISP will be released “today”)
  - [http://www.cs.utah.edu/~yuyang/inspect](http://www.cs.utah.edu/~yuyang/inspect)
- May need to obtain libssl-dev
- Need Ocaml-3.10.2 or higher
- Remove the contents of the “cache directory” autom4te.cache in case “make” loops

- bin/instrument file.c
- bin/compile file.instr.c
- inspect –help
- inspect target
- inspect –s target
The demos to follow will show that these ideas do work!!

DEMO 1 : Seq C program verification

DEMO 2 : Inspect

DEMO 3 : ISP