



## Performance / Memory Improvements

Chapel Team, Cray Inc.

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## Improved Memory Management of Records

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## Improved Memory Management of Records



### Background:

- Memory leaks are a general problem in Chapel programs
  - Primer example fileIO.chpl was leaking close to 1GB
  - Initial language design assumed efficient distributed GC
    - this remains an open research problem

### This Effort:

- Reworked memory management for user records
  - Internal record types were left unmodified



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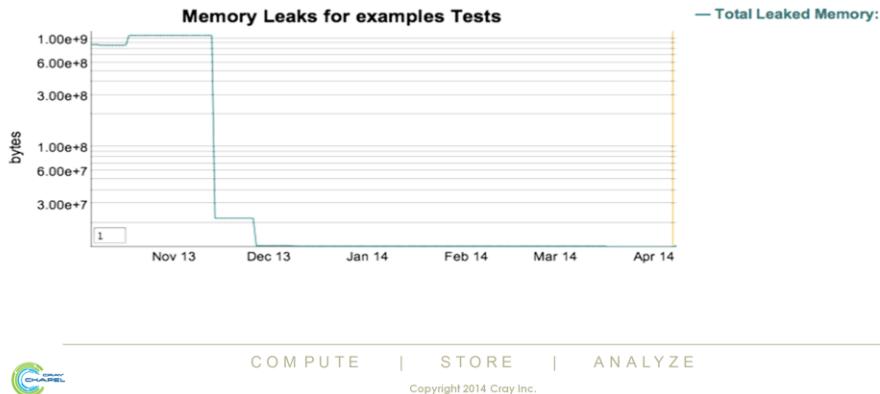
- Chapel's domain and array types are an example of an internal record type that was unmodified by this change; today they are treated specially. Over time, the goal is to treat them increasingly less specially.
- Other examples of internal record types include sync/single variables

## Improved Memory Management of Records



### Impact:

- User-defined record types now manage memory “correctly”
  - e.g., all fileIO.chpl leaks were eliminated
- significant overall reduction in leaked memory



- It should be noted that the memory leaks graph shown here does not track leaks of strings (all Chapel strings are currently leaked). A current effort is converting Chapel strings to records to make them less a special case and to benefit from this work.

## Improved Memory Management of Records



- **Defining Chapel's User-Managed Memory (UMM) Model**

- Closely follows the C++ memory-management model
- Relies on "hooks" that allow user code to perform memory-management tasks
- Default-constructor, copy-constructor, assignment-operator, destructor
  - Compiler supplies default implementations for these functions

- **Updated the compiler to insert all hook calls correctly**

- Supports reference-counting and other MM schemes
- Required only for user-declared variables and fields (not temporaries)
- 'const ref' optimization is applied where appropriate



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## Improved Memory Management of Records



### Next Steps:

- Enable a more natural coding style
  - Call user overrides of default constructors
  - Rename "initCopy" using the constructor naming convention.
- Propagate changes to internally-defined record types
  - This should drive remaining leaks to zero.

### Future Work:

- Implement the new constructor model
  - Support calling constructors as "ordinary functions"
  - Avoid double-initialization
  - Eliminate the need for an initialize() function
- Implement rvalue-reference argument intents and binding
  - Support move-constructor, move-assignment and similar memory reuse



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## Improved Program Startup

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## Improved program startup



**Background:** Multilocale startup costs rose significantly in v1.8

- New locale model infrastructure added initialization overhead
- Original design was not scalable
  - idioms were either serial or created *numLocales* tasks

**This Effort:** Spawn tasks on all the locales only once during

initialization and do so in a scalable manner

- Refactored locale-private variable initialization
  - Only turn on task table initialization when requested
- Use a single coforall+on over all locales for initialization
  - Only creates a task on the remote locale



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- The original startup design tried to avoid requiring 2 tasks and possibly 2 threads per locale, which is why it avoided using a coforall+on, as that results in an optimization that creates a single non-blocking task on each of the remote locales, all of which must synchronize with locale 0, thereby requiring an additional task. Unfortunately, under normal operation, this would result in *numLocales* tasks being created on locale#0.
- This series of commits combined defaultDist and rootLocale initialization into the initOnLocales iterator, moved memory tracking initialization into the runtime, and disabled task table initialization unless requested explicitly. We also decided to relax the minimum tasks requirement and use a coforall+on to initialize data on all the locales.

## Improved program startup



### Impact:

- Significant reduction in communications during program startup
  - Program startup times reduced by 10-15% in practice
  - Communication counts reduced significantly

| Startup costs for 5 locales      | v 1.7 | v 1.8 | v 1.9 |
|----------------------------------|-------|-------|-------|
| 'on's initiated from locale 0    | 8     | 12    | 4*    |
| • no task created                | 4     | 4     | 4     |
| • non-blocking                   | 0     | 0     | 4     |
| 'get's from locale 0             | 7     | 50    | 21    |
| 'put's to locale 0               | 2     | 2     | 4     |
| 'on's initiated from locale != 0 | 0     | 40    | 1     |



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A nightly test was added to track start-up communication counts.

Details regarding communication counts:

- on from locale 0: barrier release (\* for atomic update, would go away with AMOs for ugni comm layer)
- on no task created: LocaleTree initialization
- on non-blocking: coforall+on for defaultDist and rootLocale initialization
- get from locale 0: data transfer
- put to locale 0: data transfer
- on from locale != 0: join for coforall+on

## Improved program startup



### Next Steps: Further reduction in communication counts

- Write a distribution that supports modular iteration over locales
  - e.g., permit developers to write:

```
forall loc in Locales ...
```

rather than:

```
coforall loc in Locales do
    on loc do
```
  - implement more efficient implementations (e.g., tree-based spawning)
- Remove *LocalesTree* in favor of the distribution above
  - Will eliminate the “fast” ones that do not create tasks
- Remove unnecessary data transfer and combine data transfers



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The ‘LocalesTree’ concept was an early, non-modularized attempt to create tree-based parallelism across locales



## Improvements to Loop Invariant Code Motion (LICM)

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## Improvements to Loop Invariant Code Motion



### Background:

LICM alias analysis was too conservative

- original implementation was simple, but had many false positives
- bug fix in 1.8 greatly increased candidates checked for aliasing
  - increased compilation time (including several timeouts)
  - prevented hoisting in certain cases, increasing execution time
- for example, variable c would *not* be hoisted in the following code

```
var a = 4;
var b = a;           // LICM assumed that a and b alias
for i in 1..10 {
    var c = a + 6;  // c will not be hoisted, since b is modified
    b += c + i;
    writeln(b);
}
```

### This Effort:

Do not check for aliases involving scalar types

- scalars cannot alias other scalars
- false aliases between scalars resulted in huge numbers of alias pairs



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The original alias analysis implementation existed because it was the simplest implementation that would detect all true aliases, but led to a lot of false positives

The intention has always been to update and improve it, but good alias analysis is a large undertaking

The original algorithm would basically search for any assignments and assume that every assignment creates an alias pair

- This wasn't too bad because we were originally only checking variables inside of loops for aliasing, but this was wrong as aliases between variables in the loop can be created outside of the loop.
- r21811 corrected this issue, but led to a drastic increase in the number of aliases which led to higher compilation times and in some cases (like DGEMM) execution performance drops

Compilation timeouts were patched with a threshold for number of aliases in r21860 but this was only a stopgap solution

The fact that aliases were detected for scalars didn't initially have a large impact

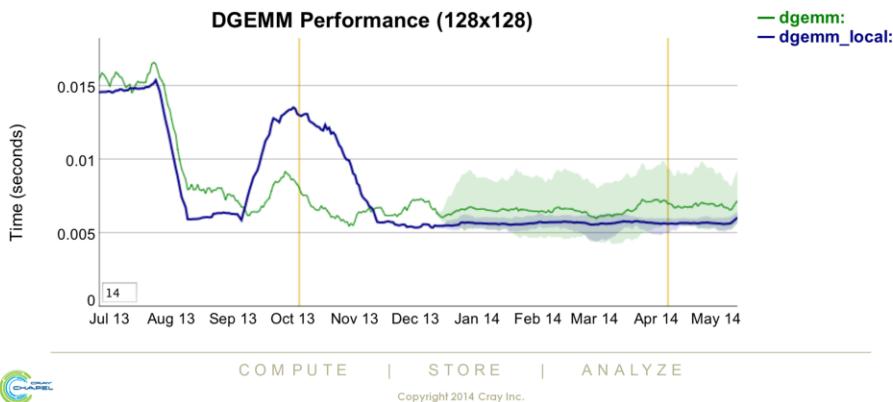
because most of our performance benefits stemmed from hoisting array metadata, and that metadata is not affected by this overly conservative alias analysis. The update from r21811 made it the case that for dgemm and programs like dgemm this overly conservative analysis became a problem

## Improvements to Loop Invariant Code Motion



### Impact:

- increased number of hoisted variables
- reduced average compilation time
  - max time for LICM went from timing out to 2 seconds
- improved execution performance



Patch to fix conservative alias analysis was r22228 on 10/30/2013

Performance impact was mostly seen for DGEMM (128x128 and 64x64)

Graph is shown with a roll period of 14 days because DGEMM is a noisy test. The important segments are that we had a steep performance benefit with LICM implementation seen before 1.9 release, and a decrease for DGEMM local close to the release, followed by a return to the all time low with the update to alias analysis.

DGEMM is over twice as fast following addition LICM and alias updates, then prior to it.

## Improvements to Loop Invariant Code Motion



### Next Steps:

- Make alias analysis less conservative
  - Chapel has very few aliases in the language, most are introduced in the IR
- Separate alias analysis from LICM
  - passes such as copy propagation and dead code elimination would benefit
- Use alias information to annotate the generated code with the **restrict** keyword when appropriate
  - helps with vectorization, OpenACC/OpenMP support
  - exposes more optimization opportunities to the backend C compilers

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Chapel has limited aliases in the language and most are added in the IR, so we should be able to track alias creation and thus determine only true aliases as they are created

- this would be significantly more accurate than the after the fact searching through assignments that we do now

Letting the backend C compiler know when variables don't alias will allow it to generate more optimized instructions, and is important for performance for OpenACC/OpenMP as well as creating code that can be vectorized.

## Loop Invariant Code Motion Bug Fixes



**Background:** LICM did not properly handle assignment by ref

- aliases of record fields were not handled properly
- for example, assignment by ref resulted in intermediate code such as:

```
tmp = &(record.field)
func(tmp); // possible changes to record.field not detected
```
- led to non-invariant records being mistakenly hoisted

**This Effort:** Handle aliases of record fields

- changes to an alias of a record's field is handled as change of the record, and the record will not be hoisted

**Impact:**

- fixed assignment by ref work for records
- no performance penalties
  - hoisting the same variables, they just had a different signature in the IR



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This bug was fixed with r22606 on 01/30/2014 and r22826 on 03/06/14

This bug was not exposed previously, it was only with the assignment by ref work that the IR had a form that made this bug hoist inappropriate expressions

r22826 fixed a related bug for tuples. Tuples are implemented as records, but there is a special primitive to access their fields that was not checked.



## Synchronization Variable Blocking Optimization

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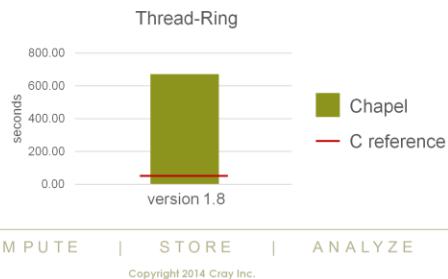
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## Sync Var Blocking Optimization



### Motivation:

- Oversubscribed multitasking tends to perform poorly relative to C
  - Results vary with different tasking layers
    - 'fifo' (the default tasking layer) was particularly bad
    - for example, thread-ring was ~11x worse than the reference version
  - The 'fifo' implementation of sync/single variables was a major problem
    - in most recent versions, threads have blocked using spin-waiting
    - previously, they had blocked using condition variables, but we switched to spin-waiting to reduce overhead for the common case when #tasks  $\approx$  #cores



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The current spin-waiting based approach is reasonable when the number of tasks is similar to the number of cores available. However, when there are a large number of tasks (thread-ring's measured problem size requires ~500), it is better to use condition variables.

## Sync Var Blocking Optimization



**This Effort:** a hybrid approach to sync var blocking for 'fifo'

- **Goal:** get the best of both worlds
  - When #tasks < #cores, block using spin-waiting
  - When #tasks ≥ #cores, block using a condition variable
- Original commit included an unintended change to thread-waiting
  - this was backed out a few weeks later

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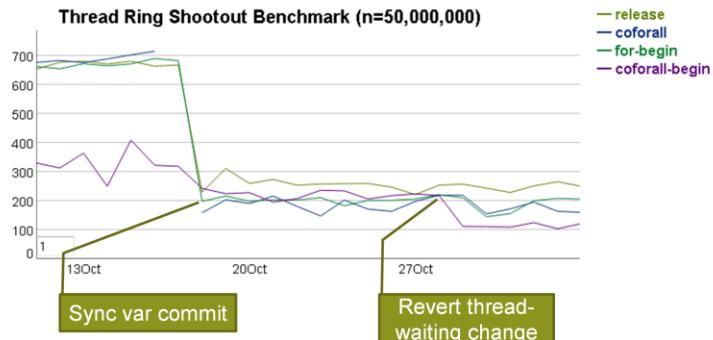
- The unplanned change was that threads, when waiting for a new task to run, inherited a similar hybrid scheme (historically, they have spin-waited as well for similar rationale; and do so today as well)
- Such a hybrid scheme could ultimately be useful, but in this implementation, we were worried about the possibility that threads would never get woken up in certain cases; and since this change wasn't intended, we backed it out
- If 'fifo' persists as a major tasking layer, this hybrid thread blocking strategy should be revisited; rather than spend more time on it, we decided to focus on Qthreads-based improvements instead

## Sync Var Blocking Optimization



### Impact (on thread-ring):

- Significantly improved thread-ring
  - ~2x faster than previous runs, only ~5x slower than reference
  - removed most disparities between different parallelization approaches



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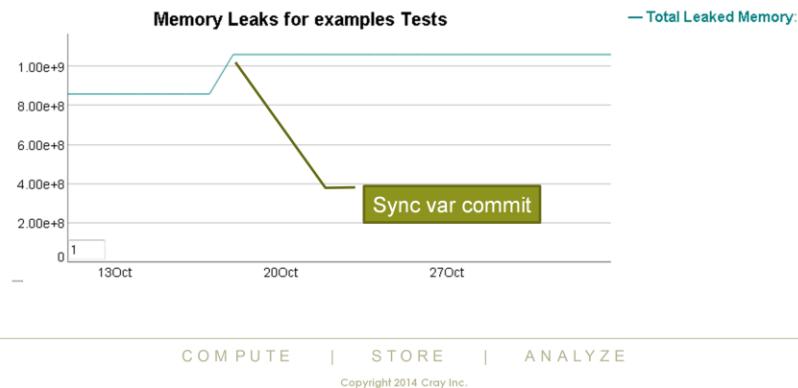


## Sync Var Blocking Optimization



### Impact (on memory):

- Chapel leaks sync variables in some situations
- Storing the condition variable used by this change made them larger
- Thus, this change increased the amount of leaked memory



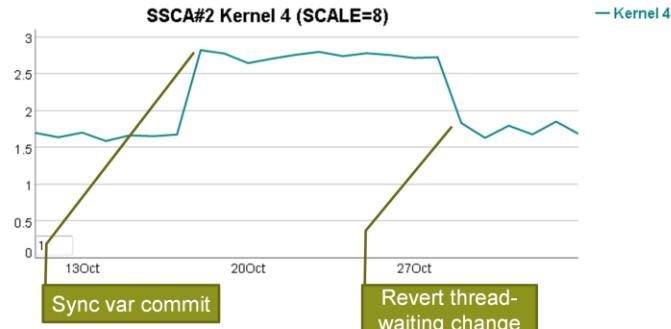
Some reclamation of this memory has occurred, but not all of it.

## Sync Var Blocking Optimization



### Impact (on other benchmarks):

- Several tests were impacted negatively by the thread-waiting change
  - e.g., SSCA#2, LULESH, spectral-norm
- When that change was reverted, so was the performance regression



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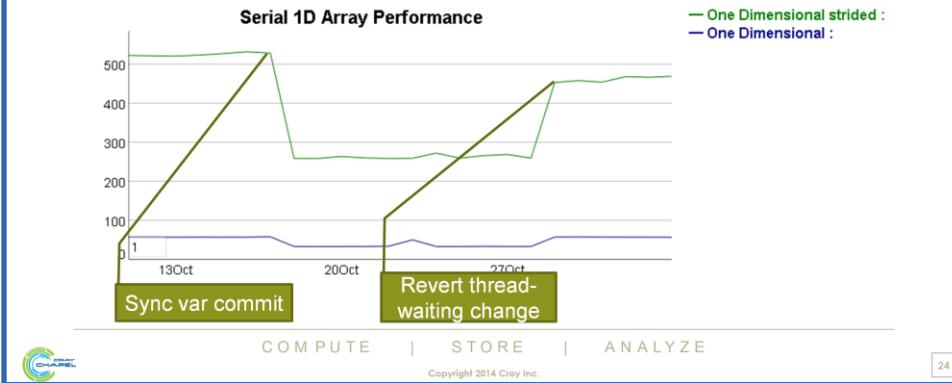
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## Sync Var Blocking Optimization



### Impact (on other benchmarks):

- Other tests benefitted from the thread-waiting change
  - e.g., Mandelbrot, serial 1D array performance, promoted op=
- When that change was reverted, so was much of the benefit

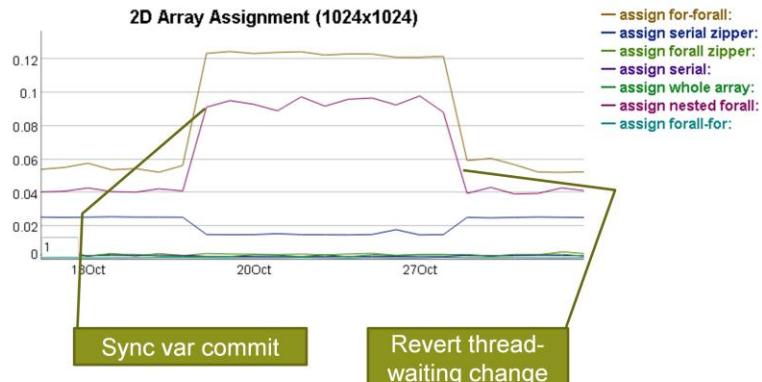


## Sync Var Blocking Optimization



### Impact (on other benchmarks):

- This test shows that a single type of computation had both gains and losses from these changes depending on how it was written



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## Sync Var Blocking Optimization



### Next Steps:

- Work toward making Qthreads the default
  - should result in performance improvements for benchmarks like thread-ring
  - ideally without performance regressions for other tests
- Close sync variable memory leaks

### Future Work:

- Consider re-implementing hybrid thread-waiting strategy
  - assuming 'fifo' continues to be used/useful



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## Optimized Serialization of Data Parallelism

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## Optimized Serialization of Data Parallelism



### Background:

- Data parallelism within a serial statement must be squashable

```
serial (here.runningTasks() > here.numCores) do
    forall i in D do ... // this loop may run serially
```
- Historically, we've created tasks without examining the serial state
  - if serialization is on, run them serially
  - otherwise run them in parallel
- This introduces unnecessary overhead when the serialization is on
  - why run  $p$  tasks of  $n/p$  iterations each instead of one  $n$ -iteration task?

### This Effort:

- If serialization is on, simply run the loop using the current task

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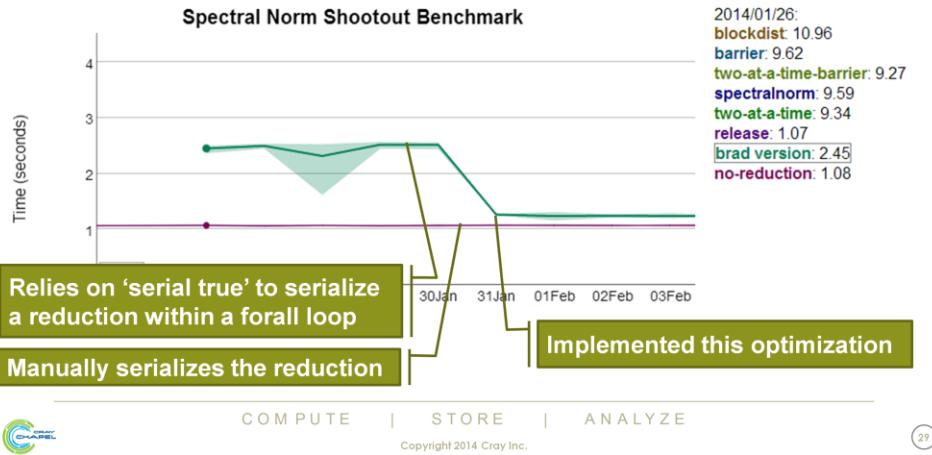
Note that while in some cases you may know statically that you will want to execute a loop in parallel and can replace the forall with a for, in constructs where we use forall under the covers, such as reductions, we need to use an serial statement.

## Optimized Serialization of Data Parallelism



### Impact:

- Idioms relying on serial statements to throttle nested parallelism saw significant improvement



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## Nested Parallelism Optimization

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## Nested Parallelism Optimization



### Background:

- policy challenge around how many tasks to use for nested parallelism

```
forall 1..n {  
    forall 1..m {  
        ...  
    }  
}
```

**Challenge:** How many tasks to use for each forall loop?

- current approach governed by *dataParIgnoreRunningTasks*
  - true: each loop uses *dataParTasksPerLocale*
  - false: each loop uses  $\min(1, \text{dataParTasksPerLocale} - \#runningTasks)$
- historically, *dataParIgnoreRunningTasks* has been true by default
  - rationale: simple model; better to oversubscribe than under

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- “uses” here is an approximation to reality, because it’s also governed by *dataParMinGranularity* which can cause fewer tasks to be used...
- clearly “better to oversubscribe than under” isn’t always true, but it felt like the less risky proposition originally...

## Nested Parallelism Optimization



### Motivation:

- too much parallelism

```
forall 1..n {  
    forall 1..m {  
        ...  
    }  
}
```

Cases like this could easily create  
 $(\text{numCores})^d$  tasks, for a  $d$ -nested loop

- the impact became more dramatic as core counts have increased



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## Nested Parallelism Optimization



### This Effort:

- flip dataParIgnoreRunningTasks to 'false' by default

```
forall 1..n {  
    forall 1..m {  
        ...  
    }  
}
```

If n is sufficiently large, the inner loop will now be run by one task

- study impact on benchmark suite



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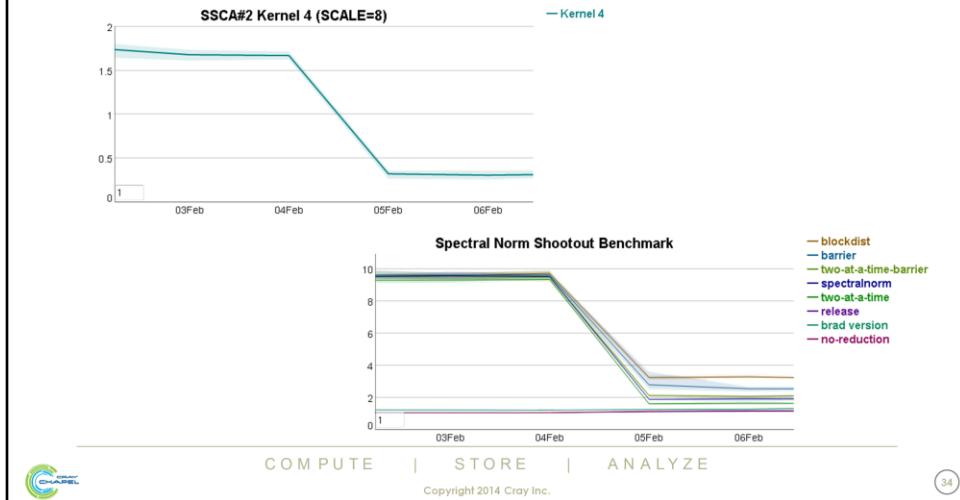
"If n is sufficiently large" means "results in enough tasks to fill all the processor cores", as governed by dataParMinGranularity

## Nested Parallelism Optimization



### Impact:

- most benchmarks were either unaffected or positively impacted



- This generated a record time for SSCA#2 on our nightly performance testing (which has since been beaten again)
- Most spectral-norm versions made use of reductions within forall statements (nested parallelism) and so improved with this change; the flat lines are versions in which the reduction was serialized and was therefore unaffected by this change.
- Additionally, it was discovered that coforall + on created an additional task on the starting locale because it does not discount itself when checking the number of tasks created. This did not dramatically affect performance when we were ignoring running tasks, but when the count mattered it became an issue for Block and Cyclic distributions, specifically. The next set of slides will address this issue.

## Nested Parallelism Optimization



### Impact:

- the current policy gives preference for tasks created earlier

```
begin {  
    // ...create n minor tasks...  
}  
forall 1..m {  
    // ...a more significant computation...  
}
```

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- In this case, should the “begun” tasks last long enough to affect the forall loop, the program will assume it cannot make use of as many tasks and so will not apply as many tasks to the forall as it would were dataParlgnore flipped.
- Of course, users can always override the default, globally or on a loop-by-loop basis

## Nested Parallelism Optimization



### Next Steps:

- explore additional mechanisms for optimizing task creation
  - compiler analysis
  - syntactic/semantic constructs
  - runtime throttling
  - inspector/executor strategies
  - profile-guided optimization
  - ...



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## Improved Task Allocation for Block Distribution

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## Improved Task Allocation for Block Distribution



### Background:

- The Block distribution's iterators use the running task count to determine the number of tasks to create on each locale
  - This count includes the task that initiated the loop if it does not block before the query is made

### This Effort:

- Ignore the initiating task if it is the only one on the locale
  - If the initiating task is the only one, we are executing in a purely data parallel manner
  - If there are other tasks, we are either using nested or unstructured parallelism, so count all tasks in an attempt to be more fair in task allocation



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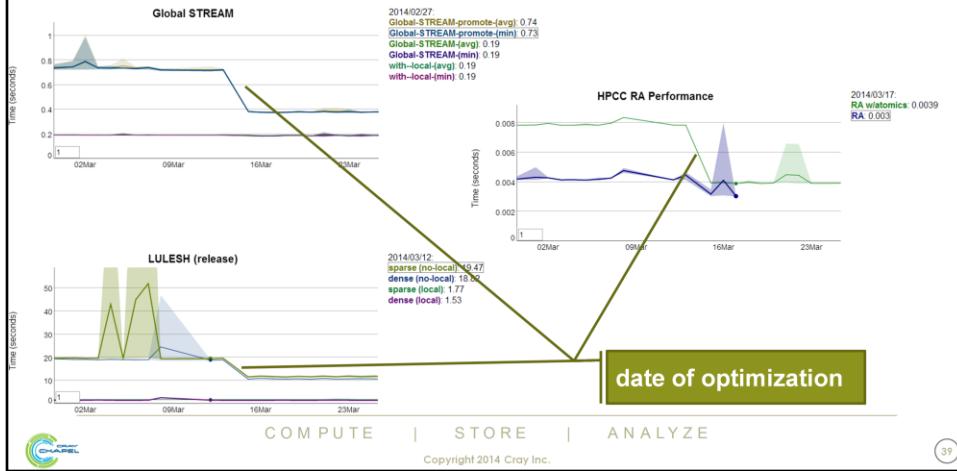
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# Improved Task Allocation for Block Distribution



## Impact:

- All available cores on the locale of the initiating task are being used
- Benchmarks using the Block distribution improved for low core-counts

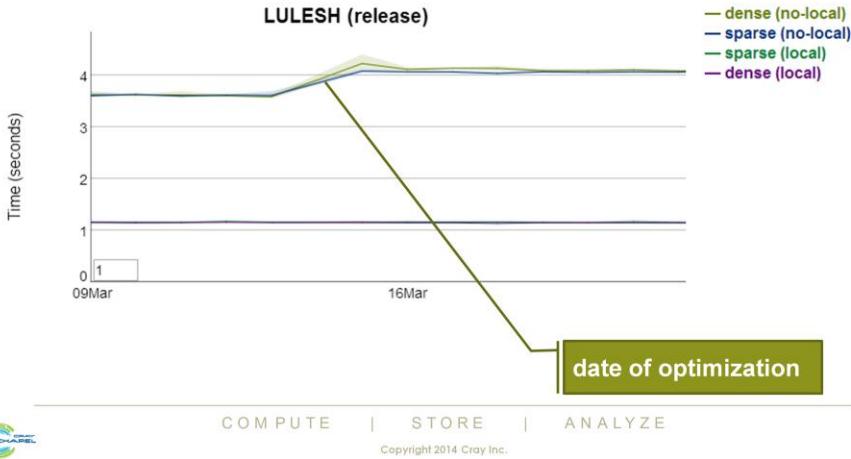


## Improved Task Allocation for Block Distribution



### Impact:

- However, some cases got worse for high core-count systems
  - Hypothesis: off-by-one errors less important than memory bandwidth



A NUMA-aware locale model may potentially help mitigate these overheads. In particular, these performance numbers are currently being gathered in a NUMA-oblivious manner.

## Improved Task Allocation for Block Distribution



### Next Steps:

- Improved tasking heuristics to get the best of both worlds
  - or, more generally, how to account for memory in choosing task counts?
- Implement a more general solution to the task counting problem
  - e.g., provide a way for tasks to request to *not* be counted in such cases



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## Whole-array Binary I/O

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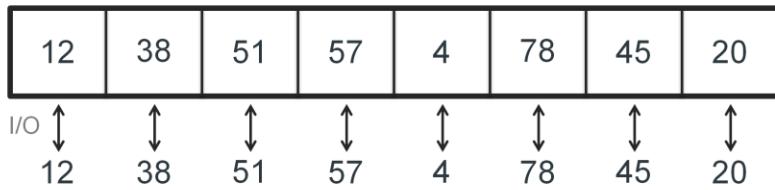
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## Whole-Array Binary I/O



**Background:** Historically, array I/O has taken many operations

- Each element results in one call



- The extra reads and writes add up quickly
- It would be nice to merge them when possible

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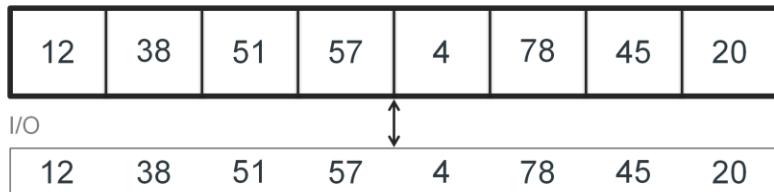
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## Whole-Array Binary I/O

**This Effort:** Binary I/O is now done with just one operation

- The whole array is read in or written out at once



- This only happens when several conditions are true:
  - Binary I/O
  - Simple element types (int, uint, real, complex, ...)
  - Byte order of the operations matches the system byte order
  - The array must be DefaultRectangular

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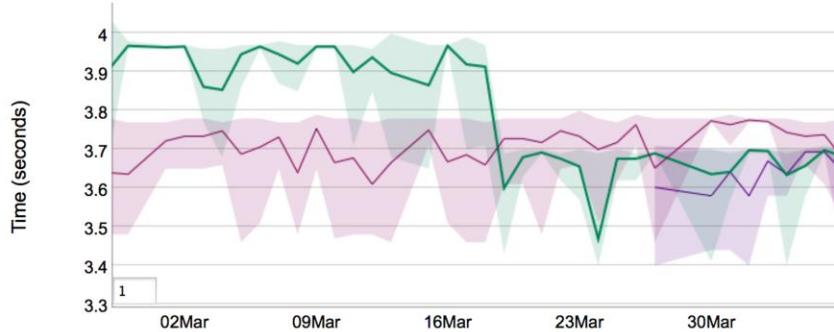
## Whole-Array Binary I/O



### Sample Impact: Mandelbrot speedup

- The test in green below gets a ~12% speedup with whole-array I/O

Mandelbrot variations



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## Whole-Array Binary I/O



**Future Work:** Relax the conditions for this capability

- Reads can work when the byte order does not match
- Add support for types composed of simple types (records, tuples)
- Add a limited form of batched writes for other distributions



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## Cleanup of noRefCount-related Module Code

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## Cleanup of noRefCount-related Module Code



## Background:

- Chapel domains/arrays are reference-counted by default
    - the current implementation is overly conservative/expensive
    - config param *noRefCount* can be used to disable reference counting
  - module code implementing reference counting is guarded
    - yet sometimes unnecessary work was done

```
proc ~_domain() {
    on _value {
        var cnt = _value.destroyDom();
        if !noRefCount then
            ...
    }
}

proc destroyDom() {
    var cnt = decRefCount();
    if !noRefCount {
        ...
    }
}
```

**This Effort:** squash extra work when reference counting is off

```
proc ~_domain() {
    if !noRefCount { ... }
}

proc destroyDom() {
    compilerAssert(!noRefCount);
    ...
}

avoid effort if noRefCount
safeguard against invoking this
```

The logo for Gray Chapel, featuring a stylized 'G' composed of green and blue concentric arcs.

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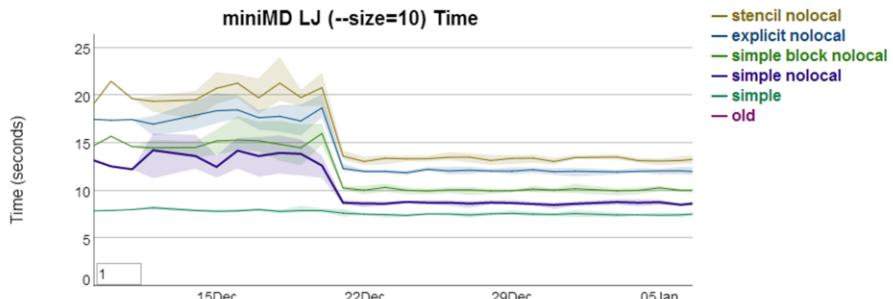
Reference counting is important because it enables reclamation of arrays and domains that are no longer used. Currently the overhead of reference counting can be significant. Setting `noRefCount=true` is a workaround for performance; it can also result in excessive memory use.

Commit 22473.

## Cleanup of noRefCount-related Module Code



**Impact:** ~30% speedup on miniMD benchmarks



### Next Steps:

- reduce the cost of reference counting for default compilations
  - decouple reference counting from argument passing semantics
  - optimize away reference counts for cases that don't require them
- deprecate the 'noRefCount' config param

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Note: miniMD benefits so much from this because it throws the `-snoRefCount` flag. Eventually, when the flag is deprecated, the goal would be to get similar performance without using a special flag.



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## Global Constant Replication Improvements

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## Global Constant Replication Improvements



### Background:

- Chapel doesn't impose an SPMD programming model on users
- Yet Chapel's implementation is SPMD
  - every SPMD image (locale) initializes the runtime stack, then...
    - locale #0 runs module initialization and user's main()
    - other locales wait for work to show up
- This provides an optimization opportunity for module-level constants:

```
module M {  
    const pi = 3.14159265; // though logically on locale #0, can be replicated  
    ...  
}
```

- in fact, the language specification promises this (Sec 26.1.5 in [v0.95](#))
- In version 1.8.0, some types were not replicated as an oversight
  - enum, imag, complex, non-default bools
  - pointed out by an academic user in the field

### This Effort: Extend replication to missing types

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- 'pi' logically lives on locale #0; but since it's invariant, each locale can store its own local copy
- Though this change can potentially have significant performance effects for such cases, we didn't see an impact in our automated testing due to lack of multi-locale performance testing as well as cases that rely on such constants



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## Removing Unnecessary Formal Temps

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## Removing unnecessary formal temps



**Background:** the Chapel compiler inserts way too many temps

- formals are one such example. The following routine

```
proc advance(nbodies: int, dt: real, B: [] Planet) { ... }
```

- generates code like:

```
static void advance(int64_t nbodies, _real64 dt, arrtype B) {  
    int64_t _formal_tmp_nbodies;  
    _real64 _formal_tmp_dt;  
    arrtype _formal_tmp_Planet;  
    _formal_tmp_nbodies = nbodies;  
    _formal_tmp_dt = dt;  
    _formal_tmp_B = B;           // mercifully, this is a shallow pointer copy  
    ... }
```

- in the best case, this is simply unfortunate noise in the generated code
  - the C compiler can optimize many such cases away for scalars
- in the worst case, it can have a negative impact
  - deep copies of record and tuple types
  - challenges to C's alias analysis

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- The historical reason for inserting formal temps conservatively (and temps in general) is to favor correctness/simplicity in the implementation first, performance afterwards. The time for performance has come, ideally without hurting simplicity (in this case, that was achieved and the result was simpler logic in the compiler).
- This code sample comes from one of our n-body codes from the Computer Language Benchmark Game:  
[test/studies/shootout/nbody/sidelnik/nbody\\_orig\\_1.chpl](#).
- arrType is a placeholder for the much longer type name used by the Chapel compiler for this array

## Removing unnecessary formal temps

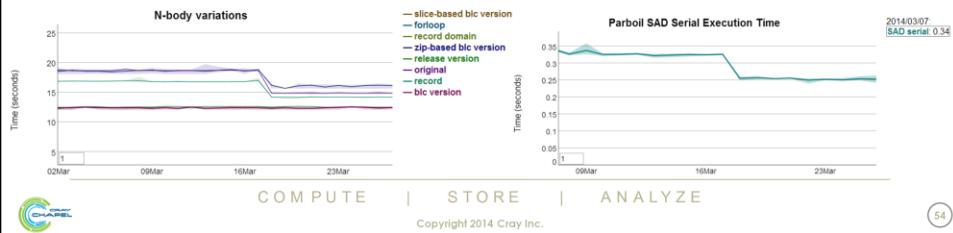


**This Effort:** eliminate most unnecessary formal temps

- motivated both by performance and code cleanup

### Results:

- code size improvements
  - e.g., 275 lines of generated code eliminated for example on previous slide
- improved const-ness checking that formal temps were masking
- fewer unnecessary copies made
  - e.g., 33% fewer lines in a simple ref counting test tracking copies/destroys
  - retired some futures flagging over-exuberant copying
- modest performance improvements and reduction in communications



- This was r22900 (and a few follow-up ones w.r.t. testing), made on March 17, 2014
- Examples of tests for which formal temps had masked illegal assignments to const records: test/functions/deitz/test\_formal\_copy1.chpl, test/nostdlib/recordpass6.chpl, test/nostdlib/recordpass7.chpl
- The reference counting test in question is test/users/ferguson/refcnt.chpl
- Bigger performance improvements arguably weren't seen in part because of a chicken-and-egg issue: we tend not to pass records around in benchmark codes because of the extra copies they've traditionally induced. For this reason, the reduction in output in the ref counting test is perhaps more telling than the performance improvements themselves.
- In the n-body graph, the light purple line marked "original" corresponds to the nbody code shown on the previous slide.

## Removing unnecessary formal temps



**Next Steps:** eliminate other unnecessary temporaries

- ref temps and call temps are two of the major cases remaining



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## Improved const-ness, remote value forwarding

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## Improved const-ness/remote value forwarding



### Background (remote value forwarding):

- An optimization to bundle read-only values with active messages
  - must be done subject to Chapel's memory consistency model
- E.g.,

```
const x = 1;
on ... {           // an active message is used to implement this on-clause
    ...x...        // naively, this reference would require a remote read of x
}
}                  // with remote value forwarding, x is bundled with the active message
```
- 'const in' args had not been r.v.f.'d as aggressively as they could be

### Background (use of 'const'):

- Marking things as 'const' improves optimization opportunities
  - Remote value forwarding is one such opportunity
- In flattening nested functions, const-ness was sometimes lost

*(Both of these cases were identified by the formal temp work)*



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- remote value forwarding = bundling read-only values with the active messages that implement on-clauses (subject to the memory consistency model)
- even if a user does not use nested functions, the compiler uses them frequently to implement task parallelism and on-clauses, so propagating const-ness across them is important

## Improved const-ness/remote value forwarding



### This Effort:

addressed both issues

- made remote value forwarding handle 'const in' arguments better
- preserved const-ness across nested functions better

### Results:

- modest reduction in communication counts for reductions
- fixed a bug future
- enabled the previously described formal temp elimination work

### Next Steps:

- look out for other opportunities for similar improvements



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- This was r22894 (and a few follow-up ones w.r.t. testing), made on March 15, 2014
- The bug future in question was test/users/vass/crash4repLclsWFlds.future



## Simplified Homogeneous Tuple Ops

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# Simplified Homogeneous Tuple Ops



## Background:

- Chapel supports operators on tuples:  
 $(1, 2, 3) + (4, 5, 6) \Rightarrow (5, 7, 9)$   
 $("hi", 1) + ("ya", 2) \Rightarrow ("hiya", 3)$
- The traditional implementation of these operators has been recursive:

```
inline proc +(a: _tuple, b: _tuple) {
    if a.size != b.size then
        compilerError("tuple operands to + have different sizes");
    if a.size == 1 then
        return (a(1)+b(1),);
    else
        return (a(1)+b(1), (...chpl_tupleRest(a)+chpl_tupleRest(b)));
}
```
- Reason:
  - In the heterogeneous case, it's difficult to declare the result type a priori
  - Elegant, general Lisp-like



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## Simplified Homogeneous Tuple Ops



### More Background:

- The generated code for this recursive approach is awful:

```
var x = (1.0, 2.0, 3.0),
    y = (4.0, 5.0, 6.0),
    z = x + y;

call_tmp = (1.0 + 4.0);
ret_to_arg_ref_tmp_ = &wrap_call_tmp;
chpl_tupleRestHelper2(1.0, 2.0, 3.0, ret_to_arg_ref_tmp_);
ret_to_arg_ref_tmp_2 = &wrap_call_tmp2;
chpl_tupleRestHelper2(4.0, 5.0, 6.0, ret_to_arg_ref_tmp_2);
call_tmp2 = *(wrap_call_tmp + INT64(0));
call_tmp3 = *(wrap_call_tmp2 + INT64(0));
call_tmp4 = (call_tmp2 + call_tmp3);
call_tmp5 = *(wrap_call_tmp + INT64(0));
call_tmp6 = *(wrap_call_tmp + INT64(1));
ret_to_arg_ref_tmp_3 = &wrap_call_tmp3;
chpl_tupleRestHelper(call_tmp5, call_tmp6, ret_to_arg_ref_tmp_3);
call_tmp7 = *(wrap_call_tmp2 + INT64(0));
call_tmp8 = *(wrap_call_tmp2 + INT64(1));
call_to_arg_ref_tmp_4 = &wrap_call_tmp4;
chpl_tupleRestHelper(call_tmp7, call_tmp8, ret_to_arg_ref_tmp_4);
call_tmp9 = *(wrap_call_tmp3 + INT64(0));
call_tmp10 = *(wrap_call_tmp4 + INT64(0));
call_tmp11 = (call_tmp9 + call_tmp10);
*(z + INT64(0)) = call_tmp;
*(z + INT64(1)) = call_tmp4;
*(z + INT64(2)) = call_tmp11;
```

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## Simplified Homogeneous Tuple Ops



### This Effort:

- Observed that the homogeneous case can be written non-recursively:

```
inline proc +(a: _tuple, b: _tuple) where chpl_TwoHomogTuples(a,b) {
    if a.size != b.size then
        compilerError("tuple operands to + have different sizes");

    var result: a.size*(a(1) + b(1)).type;
    for param d in 1..a.size do
        result(d) = a(d) + b(d);

    return result;
}
```

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- The reason this case can be done is because we can determine the type of a single component and then declare a homogeneous tuple of that type
- This commit was made in r22475, December 21<sup>st</sup> 2013

## Simplified Homogeneous Tuple Ops



### This Effort:

- Now we get much cleaner generated code:

```
var x = (1.0, 2.0, 3.0),  
    y = (4.0, 5.0, 6.0),  
    z = x + y;
```

- Results in the following code:

```
call_tmp = (1.0 + 4.0);  
call_tmp2 = (2.0 + 5.0);  
call_tmp3 = (3.0 + 6.0);  
*(z + INT64(0)) = call_tmp;  
*(z + INT64(1)) = call_tmp2;  
*(z + INT64(2)) = call_tmp3;
```

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## Simplified Homogeneous Tuple Ops



### Next Steps:

- What language changes would enable a non-recursive approach for the heterogeneous case too?



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## Copy Propagation Reimplemented

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## Copy Propagation Reimplemented



### • The Problem:

- Old CP implementation did not track assignment through references
- Instead, only killed candidate pairs when a reference was created
- Had the potential to produce incorrect results

```
a = 1;           // Creates candidate pair (a, 1)
int* ap = &a; // Kills candidate pair
a = 2;           // New candidate pair (a, 2)
*a = 3;          // Ignored
b = a;           // Substitutes b = 2.  Oops!
```

- But, not many references in older code, so this bug remained hidden
- New assignment signature uses references more extensively
- Uncovered a similar bug in Loop-Invariant Code Motion

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## Copy Propagation Reimplemented



### • The Solution:

- New CP tracks references across an entire function
- Candidate pairs are killed when the content of a reference is updated

```
a = 1;           // Creates candidate pair (a, 1)
int* ap = &a; // Noted in a previous pass
a = 2;           // New candidate pair (a, 2) kills (a, 1)
*a = 3;          // Kills candidate pair (a, 2)
b = a;           // No substitution
```

- Bonus: We now propagate literals as well as constant values
- 10% reduction in generated code size

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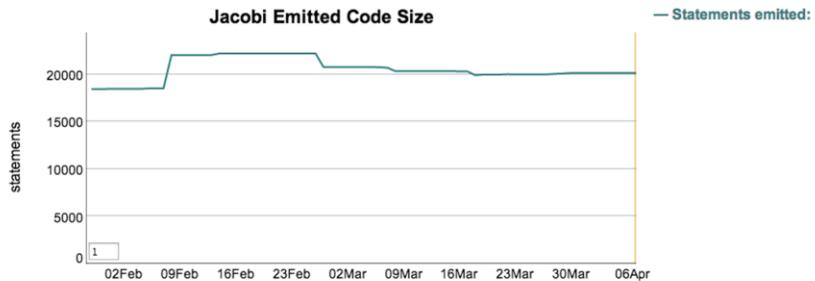
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## Copy Propagation Reimplemented



### Next Steps

- Track references dynamically
- Track updates through references



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