Parallel Programming with Lisp for Performance

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Introduction

- SMP has arrived in Common Lisp implementations (ABCL, Allegro, clisp, Clozure, ECL, LispWorks, SBCL, …)

- Parallel programming means not only starting lots of threads, but also synchronizing them.

- So far LispWorks seems to provide the richest library of synchronization mechanisms. Therefore, in this presentation, the focus is on LispWorks.
Why is parallel programming hard?

• Consider this simple program:

(defun count-3s (list)
  (let ((count 0))
    (dolist (number list)
      (mp:process-run-function "count numbers" ()
        (lambda () (when (= number 3) (incf count))))
      count))
Why is parallel programming hard?

Consider this simple program:

```
(defun count-3s (list)
  (let ((count 0))
    (dolist (number list)
      (mp:process-run-function "count numbers" ()
        (lambda () (when (= number 3) (incf count)))))
    count))
```
Why is parallel programming hard?

• Consider this simple program:

```lisp
(defun count-3s (list)
  (let ((count 0))
    (dolist (number list)
      (mp:process-run-function "count numbers" ()
        (lambda () (when (= number 3) (incf count))))
    count))
```
Why is parallel programming hard?

• Consider this simple program:

(defun count-3s (list)
  (let ((count 0))
    (dolist (number list)
      (mp:process-run-function "count numbers" '()
        (lambda () (when (= number 3) (incf count))))
    count))
Why is parallel programming hard?

• Consider this simple program:

(defun count-3s (list)
  (let ((count 0))
    (dolist (number list)
      (prun (lambda () (when (= number 3) (incf count))))
      count))
Why is parallel programming hard?

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  (defun count-3s (list)
    (let ((count 0))
      (dolist (number list)
        (prun (lambda () (when (= number 3) (incf count))))
        count))

- Combinatorial explosion of the computational state space:
  - Accesses to the count variable can occur at the same time.
  - We do not know when all the different computations are done.
  - In Common Lisp, iterations are also not guaranteed to use fresh bindings.
Why is parallel programming hard?

- (defun count-3s (list)
  (let ((count 0)) (iteration-count 0)
    (lock (mp:make-lock)))
  (dolist (number list)
    (let ((number number))
      (prun (lambda ()
        (mp:with-lock (lock)
          (when (= number 3) (incf count))
          (incf iteration-count))))))
  (loop until (= iteration-count (length list))
    count)
Why is parallel programming hard?

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  (let ((count 0)) (iteration-count 0)
    (lock (mp:make-lock))
    (dolist (number list)
      (let ((number number))
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          (mp:with-lock (lock)
            (when (= number 3) (incf count))
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          (incf iteration-count))))))
  (loop until (= iteration-count (length list)))
  count)

take the lock
Why is parallel programming hard?

- (defun count-3s (list)
  (let ((count 0)) (iteration-count 0)
    (lock (mp:make-lock))
    (dolist (number list)
      (let ((number number))
        (prun (lambda ()
          (mp:with-lock (lock)
            (when (= number 3) (incf count))
            (incf iteration-count)))))
      (loop until (= iteration-count (length list)))
    count)
Why is parallel programming hard?

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  (let ((count 0)) (iteration-count 0)
    (lock (mp:make-lock)))
  (dolist (number list)
    (let ((number number))
      (prun (lambda ()
        (mp:with-lock (lock)
          (when (= number 3) (incf count))
          (incf iteration-count)))))
    (loop until (= iteration-count (length list)))
  count)

- Result is now correct, but this is horribly inefficient code.

- Particularly, there is no parallelism here.
What does that mean?

• Sequential programs are much easier to understand.

• Primary goal of parallel programming: efficiency!!!

• If you don’t need efficiency, don’t go parallel.
Concurrency

• Important abstractions:
  Actor model, event loops, threads, locks, transactions, …
Concurrent applications solves problems that are inherent in their domain. This is independent from the availability of parallel hardware! Single-core processors would have to solve these issues as well!
Parallelism

• Important abstractions:
  Parallel loops, data parallelism, fork/join, mapreduce, …
Parallelism

- Parallel programming helps improving performance. This is independent from the presence of concurrency in the applications! Single-core processors would just execute a sequential program!
Concurrent vs. parallelism

- Solutions that are good for concurrent problems may be detrimental for parallelism and vice versa.
Problems with locking...

- This cannot happen with STM!
Problems with locking...

• Solution: Take all locks always in the same order. (May be incorrect depending on problem domain, but is usually correct when only performance matters.)
Problems with STM...

- This cannot happen with locks!
Problems with STM...

• Solution: Add heuristics and back-off strategies. (This hurts performance even more, so may not be acceptable if you use parallelism for performance!)
Example: Task parallelism

• (defun count-3s (vector)
   (labels ((recur (start end)
      (let ((length (- end start)))
        (case length
          (0 0)
          (1 (if (= (svref vector start) 3) 1 0))
          (t (let* ((half (ash length -1))
           (middle (+ start half)))
             (let (left right)
               (spawn (left) (recur start middle))
               (setq right (recur middle end))
               (sync)
               (+ left right))))))))
   (recur 0 (length vector))))
Parallelism for performance: Amdahl’s Law

- $n$: number of threads
- $P$: parallel fraction of the algorithm
- $(T_n)$: time the algorithm takes on $n$ threads
- $(S_n)$: speedup on $n$ threads

\[
(T_n) = (\text{let} \ ((\text{seqT} (* (T 1) (- 1 P))))
       \quad (\text{parT} (* (T 1) P)))
       \quad (+ \text{seqT} (/ \text{parT} n)))
\]

\[
(S_n) = (/ 1 (+ (- 1 P) (/ P n)))
\]

\[
(S \infty) = (/ 1 (- 1 P))
\]

- Examples: $P = 90\% \Rightarrow$ maximum speedup = 10
- $P = 80\% \Rightarrow$ maximum speedup = 5
Parallelism for performance: Gustafson’s Law

- \( a \): sequential time
- \( b \): parallel time
- \( P \): number of processors

\[
T(P) = (+ a (* P b))
\]
\[
S(P) = (/ (+ a (* P b)) (+ a b))
\]

- \( \alpha = (/ a (+ a b)) \)
\[
S(P) = (+ \alpha (* P (- 1 \alpha)))
= (- P (* \alpha (- P 1)))
\]
Parallelism for performance

- Sequential performance is important! The better the sequential section performs, the better the gains from parallelization!
General performance considerations in Lisp

- Avoid consing / memory management
  => dynamic extent / stack allocation
  => boxed vs. unboxed types
  => 64bit vs. 32bit Lisp implementations
  => control the garbage collector

- Identify and optimize fast paths

- Inline declarations

- Optimization & type declarations

- typed aref, int32 operations (LispWorks-specific)
Recipe for parallelization

- Identify the parallelism
- Identify the dependencies
  - Identifying parallelism is relatively easy. Identifying dependencies is harder. Handling dependencies efficiently is even harder.
  => Know your toolbox!
Synchronization toolbox in LispWorks

- Mailboxes
- Locks, incl. shared locks
- Hash tables, vectors with fill pointers
- Barriers, semaphores, condition variables, atomic operations, memory order synchronization
- Thread-local memory allocation
- Garbage collector freezes all processes
Example: fluidanimate

- One of the benchmarks in the PARSEC benchmark suite
- Implementation of the Smoothed-particle Hydrodynamics method
Example: fluidanimate
Example: fluidanimate
Example: fluidanimate
Example: fluidanimate
Example: fluidanimate
Example: fluidanimate
Fluidanimate: data structures

- `(defstruct (vec3 (:constructor make-vec3 (x y z))
                (:constructor make-zero-vec3 ()))
  (x 0.0 :type float-type)
  (y 0.0 :type float-type)
  (z 0.0 :type float-type))

- `(defstruct (cell (:constructor make-cell ()))
  (p (create-array 16 'make-zero-vec3 :element-type 'vec3)
      :type (array vec3 (16))))
  (hv (create-array 16 'make-zero-vec3 :element-type 'vec3)
       :type (array vec3 (16))))
  (v (create-array 16 'make-zero-vec3 :element-type 'vec3)
      :type (array vec3 (16))))
  (a (create-array 16 'make-zero-vec3)
      :type simple-vector))
  (density (make-array 16 :initial-element 0.0)
            :type simple-vector))`
Fluidanimate: main loop

(defun advance-frame ()
  (declare #.*optimization*)
  (let ((num-grids (num-grids)))
    (declare (fixnum num-grids))
    (parallel-for num-grids ‘clear-particles-mt)
    (parallel-for num-grids ‘rebuild-grid-mt)
    (parallel-for num-grids
      ‘init-densities-and-forces-mt)
    (parallel-for num-grids ‘compute-densities-mt)
    (parallel-for num-grids ‘compute-densities-2-mt)
    (parallel-for num-grids ‘compute-forces-mt)
    (parallel-for num-grids ‘process-collisions-mt)
    (parallel-for num-grids ‘advance-particles-mt)))
Fluidanimate: example step

\[
\text{(defun compute-forces-mt (i)}
\quad \text{(declare #.*optimization*)}
\quad \text{(loop over each cell in (aref grids i) do)}
\quad \quad \text{(loop over each p in cell do)}
\quad \quad \quad \text{(loop over each neighbor of cell do)}
\quad \quad \quad \quad \text{(loop over each np in neighbor do)}
\quad \quad \quad \quad \quad \text{(when (< (index np) (index p)))}
\quad \quad \quad \quad \quad \quad \text{(let ((acc (compute-acc p np)))}
\quad \quad \quad \quad \quad \quad \quad \text{(if (borderp cell)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \text{(loop)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{for old = (svref (cell-a cell) p)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{for new = (vec3+ old acc)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{until (compare-and-swap (svref (cell-a cell) p) old new))}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{(vec3+= (svref (cell-a cell) p) acc))}
\quad \quad \quad \quad \quad \quad \quad \text{(if (borderp neighbor)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \text{(loop)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{for old = (svref (cell-a neighbor) np)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{for new = (vec3- old acc)}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{until (compare-and-swap (svref (cell-a cell) np) old new))}
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{(vec3-= (svref (cell-a cell) np) acc)))))))))
\]
Fluidanimate: main challenges

• When translating from C++ to Lisp, we encountered the following performance challenges:
  • Too much consing.
  • Controlling the garbage collector.
  • Getting synchronization right.
  • Abstracting away the parallelization.
Fluidanimate: Too much consing.

- At the heart of the algorithm, lots of uses of vec3 operations:
  - `(defun vec3+ (v1 v2)
    (make-vec3 (+ (vec3-x v1) (vec3-x v2))
               (+ (vec3-y v1) (vec3-y v2))
               (+ (vec3-z v1) (vec3-z v2))))`
  - Same for subtraction, negation, multiplication, division.
  - No matter the type and optimization declarations, there are just far too many intermediate results on the heap.
Fluidanimate: Too much consing - solution.

(defstruct (vec3 (:constructor make-vec3 (x y z)) (:constructor make-zero-vec3 () (:constructor vec3+ (v1 v2 &aux (x (+ (vec3-x v1) (vec3-x v2))) (y (+ (vec3-y v1) (vec3-y v2))) (z (+ (vec3-z v1) (vec3-z v2))))) (:constructor vec3* (v1 s &aux . . .)) . . .) (x 0.0 :type float-type) (y 0.0 :type float-type) (z 0.0 :type float-type))
Fluidanimate: Too much consing - solution.

• Now the return values can be declared with dynamic-extent at the receiving side, and will therefore be allocated on the stack, not on the heap.

• However, intermediate results must all be named.

• Inline functions with calls to such constructors may also work with dynamic-extent declarations and result stack allocation.
Fluidanimate:
Stack allocation for intermediate results would be nice.

...  
(\texttt{vec3*= acc pressure-coeff})  
(\texttt{vec3*= acc (/ (* hmr hmr) dist)})  
(\texttt{vec3*= acc (- (+ (svref cell-density cell) j))})  
\hspace{1cm} \texttt{(svref cell-density neigh) i)))  
\hspace{1cm} \texttt{double-rest-density})  
(\texttt{let* ((cell-v (aref (cell-v cell) j))})  
\hspace{1cm} (\texttt{neigh-v (aref (cell-v neigh) i))})  
\hspace{1cm} (\texttt{ddd (vec3- neigh-v cell-v))})  
(\texttt{declare (vec3 cell-v neigh-v ddd)})  
\hspace{1cm} (\texttt{dynamic-extent ddd})  
(\texttt{vec3*= ddd viscosity-coeff})  
(\texttt{vec3*= ddd hmr})  
(\texttt{vec3+= acc ddd})  
(\texttt{vec3/= acc (* (svref (cell-density cell) j)})  
\hspace{1cm} \texttt{(svref (cell-density neigh) i)))})  
\hspace{1cm} \texttt{...
return-with-dynamic-extent

- My wish:

- `(defun vec3+ (v1 v2)
  (return-with-dynamic-extent
   (make-vec3 (+ (vec3-x v1) (vec3-x v2))
   (+ (vec3-y v1) (vec3-y v2))
   (+ (vec3-z v1) (vec3-z v2))))`

- [Also: dynamic extent for typed aref vectors!]
Fluidanimate: Abstracting away parallelization.

- `(defun parallel-for (numgrids function)  
  (loop for i below numgrids  
    collect (mp:process-run-function  
      (string function) `() function i)  
    into processes finally  
    (mapc `mp:process-join processes)))`

- OK when numgrids = available processors.

- Otherwise distribute grids evenly over available processor. (Easy.)

- However, what if there is load imbalance?  
  => Employ work stealing!
What is work stealing?

• Each thread has a deque, pushes and pops work on one end; steals work from other queues on other ends; stealing occurs only when own deque is empty => stealing is a rare event, work is mostly done on local data.
Work stealing with fork/join computations. (Inspired by Cilk, here with claws.)

- Primitives:
  - spawn = add work to local deque
  - sync   = ensure all previously local work is done
  - reset-workers = create n worker threads
  - all stealing happens in the background
parallel-for with fork/join

- (defun parallel-for (n function)
  (labels ((recur (k start end)
    (let ((diff (- end start)))
      (case diff
        (0)
        (1 (funcall function start))
        (t (let* ((half (ash diff -1))
         (middle (+ start half))
         (spawn () (recur middle end))
         (recur start middle))
         (sync)))))
      (recur 0 n)))

- aka divide and conquer
Example: sequencing pipelines

- DNA sequencing \approx \text{string pattern matching}

- Sequencing pipelines:
  1. Match reads against a reference
  2. Analyse matched reads
DNA ≈ Code

- DNA: AGGCTACTTAAAT… => genome
- RNA: GUGCAUUGAGUA… => transcriptome
- Protein: V H L T P E E E K…
DNA Sequencing $\approx$ Pattern matching

Alignment $\approx$
Where do the reads match in the reference?
SAM/BAM Files

- `{ QNAME: "ERR091575.2", FLAG: 16, RNAME: "chr13", POS: 100163268, MAPQ: 37, CIGAR: 100M, RNEXT: "*", PNEXT: 0, TLEN: 0, SEQ: "GCTTCTCCTGAGATCATCG…", QUAL: "DDDDDDDDDDDEDEDDDDDD…", XT: "U", NM: 3, X0: 1, X1: 0, XM: 3, XO: 0, XG:0, MD: "25C17A55T0", RG: "group1" }`
CIGAR Strings

<table>
<thead>
<tr>
<th>Op</th>
<th>BAM</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>0</td>
<td>alignment match (can be a sequence match or mismatch)</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>insertion to the reference</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>deletion from the reference</td>
</tr>
<tr>
<td>N</td>
<td>3</td>
<td>skipped region from the reference</td>
</tr>
<tr>
<td>S</td>
<td>4</td>
<td>soft clipping (clipped sequences present in SEQ)</td>
</tr>
<tr>
<td>H</td>
<td>5</td>
<td>hard clipping (clipped sequences NOT present in SEQ)</td>
</tr>
<tr>
<td>P</td>
<td>6</td>
<td>padding (silent deletion from padded reference)</td>
</tr>
<tr>
<td>=</td>
<td>7</td>
<td>sequence match</td>
</tr>
<tr>
<td>X</td>
<td>8</td>
<td>sequence mismatch</td>
</tr>
</tbody>
</table>

- 10H30M15I32M8H
Typical computation on CIGAR Strings

• (defun sum-referenced (cigar)
   (loop for (key . val) in cigar
     if (member key `(:M :D :N := :X))
     sum val fixnum))
Better version

- (define-symbol-macro cigar-ops “MIDNSHPX=“)
  (defconstant +min-cigar-op+
    (reduce ‘min cigar-ops :key ‘char-code))
  (defconstant +max-cigar-op+
    (reduce ‘max cigar-ops :key ‘char-code))

- (declare (inline cigar-index))

(defun cigar-index (char)
  (declare (base-char char)
    (optimize (speed 3) (space 0) (debug 0) (safety 0)
      (compilation-speed 0) (fixnum-safety 0)))
  (- (char-code char) +min-cigar-op+))
Better version

- (defun make-reference-table ()
  (let ((table (make-array (1+ (- +max-cigar-op+
                              +min-cigar-op+))
                              :initial-element #.(code-char 0)
                              :element-type 'base-char
                              :allocation :long-lived
                              :single-thread t)))
    (flet ((set-reference (char))
           (setf (sbchar table (cigar-index char)) #.(code-char 1)))))
    (set-reference #\M)
    (set-reference #\D)
    (set-reference #\N)
    (set-reference #\=)
    (set-reference #\X)))
Better version

• (declare (notinline sum-referenced))

(defun sum-referenced (cigar)
  (declare (list cigar)
    (optimize (speed 3) (space 0) (debug 0) (safety 0)
      (compilation-speed 0) (fixnum-safety 0)))
  (let ((table (load-time-value (make-reference-table) t)))
    (loop for (key . value) in cigar
      for keychar = (sbchar (symbol-name key) 0)
      for factor = (char-code (sbchar table keychar))
      sum (* factor value) fixnum)))
Summary

• Distinguish concurrency vs. parallelism

• If you want parallelism for performance, you need to care about sequential performance as well.

• There is no single parallel programming paradigm that fits all problems.

• Parallel Lisps should provide building blocks for domain-specific parallel constructs (or just constructs suited for different domains).
What next?

- Work stealing (Intel Cilk Plus, TBB)
- Intel Cilk Plus: CEAN (Paralation Lisp, APL)
- Intel CnC (incl. distributed processing)
- MPI
- PGAS: Chapel, Fortress, X10
Thank You
Why are Lisp programs hard to parallelize?

- (defun count-3s (list)
  (if (null list)
    0
    (+ (if (= (car list) 3) 1 0)
       (count-3s (cdr list))))))
Why are Lisp programs hard to parallelize?

• (defun count-3s (list)
   (if (null list)
       0
       (+ (if (= (car list) 3) 1 0)
           (count-3s (cdr list)))))

• Lists from cons cells are an inherently sequential data structure.
Mailboxes out of condition variables

• (defstruct mailbox
   (cond (mp:make-condition-variable))
   (lock (mp:make-lock))
   (list ‘()))

(defun mailbox-read (mailbox)
  (mp:with-lock ((mailbox-lock mailbox))
    (loop until (mailbox-list mailbox) do
      (mp:condition-variable-wait
       (mailbox-cond mailbox) (mailbox-lock mailbox)))
    (pop (mailbox-list mailbox))))

(defun mailbox-send (mailbox object)
  (mp:with-lock ((mailbox-lock mailbox))
    (push object (mailbox-list mailbox))
    (mp:condition-variable-signal (mailbox-cond mailbox))))
Barriers

- (defun count-3s (vec &aux (length (length vec)))
  (loop with block-size = (ceiling length *threads*)
     with mailbox = (mp:make-mailbox)
     with barrier = (mp:make-barrier *threads*)
   for start below length by block-size
   for end = (min (+ start block-size) length) do

     (prun (lambda (start end)
              (loop for i from start below end do
                   (setf (svref vec i) (if (= (svref vec i) 3) 1 0)))
                    (mp:barrier-wait barrier)
                    (mp:mailbox-send mailbox
                     (loop for i from start below end sum (svref vec i)))))

   finally (return (loop repeat *threads* sum (mp:mailbox-read mailbox))))
Fork/join + work stealing

• Fork/join and work stealing are independent of each other. (For example, work stealing schedulers also useful for futures, actors, ...)

• Literature shows optimal theoretical performance and space bounds when fork/join and work stealing are combined. (Blumofe, Leiserson, Scheduling Multithreaded Computations by Work Stealing, FOCS’94 & J. ACM’99)

• Confirmed by practical experience (Cilk, TBB, Java fork/join, ...) (Frigo, Leiserson, Randall, The Implementation of the Cilk-5 Multithreaded Language, PLDI’98)

• Work stealing works well until a certain number of processor cores. (Dinan et al., Scalable Work Stealing, SC’09)
Library-style work stealing (TBB, Java fork/join, ...)

- int fib (int n) {
  int f1 = fork(fib(n-1));
  int f2 = fork(fib(n-2));
  join();
  return f1+f2;
}
Cilk-style work stealing

- int fib (int n) {
  int f1 = fork(fib(n-1));
  int f2 = fork(fib(n-2));
  join();
  return f1+f2;
}
The continuation of a fork...

```c
• int fib (int n) {
    int f1 = fork(fib(n-1));
    int f2 = fib(n-2);
    join();
    return f1+f2;
}
```
...and the continuation of a join.

```c
• int fib (int n) {
    int f1 = fork(fib(n-1));
    int f2 = fib(n-2);
    join();
    return f1+f2;
}
```
Cilk-style vs. library-style work stealing

- Cilk-style guarantees optimal performance and optimal space bounds
  - ...requires efficient representation of continuations & compiler support
- Library-style guarantees only optimal performance, no space bounds
  - ...requires trickery in join step to support better space bounds (TBB)
- (Guo, Barik, Raman, Sarkar, Work-first and help-first scheduling policies for async-finish task parallelism, IPDPS’09)