Reusable Work Seeking Parallel Framework for Ada 2005

(*and Beyond)

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Presentation Outline

- Describe generic classification
  - Iterative vs Recursive
  - Work Sharing vs Work Seeking
  - Reducing vs Non-Reducing
- Describe Work Sharing, Work Stealing, Work Seeking
- Iterative & Recursive Parallelism Examples
- Pragma ideas for further simplification
- Lessons Learned, Affinity, Worker Count, Work Budget
- Briefly discuss how generics could be applied to Battlefield Spectrum Management
- Performance Results

Parallel Generics Implemented

			Iterative Parallelism	Recursive Parallelism
Work Sharing (without load balancing)	Non-Reducing		✓	✓
	Reducing	Elementary	✓	✓
		Composite	✓	✓
Work Seeking (load balancing)	Non-Reducing		✓	✓
	Reducing	Elementary	✓	✓
		Composite	✓	✓

Iterative usage

- Speeding up loops
  - Best applied to ”for” loops, where number of iterations known before starting parallelism
- Example usage
  - Solving matrices, partial differential equations
  - Determining if a number is prime
  - Processing a large number of objects
  - Processing a small number of ”big” objects

Recursive usage

- Processing recursive (tree) data structures
  - Binary trees, Red/Black Trees
  - N-way trees
- Recursive algorithms (e.g. Fibonacci)

  Fibonacci (X)

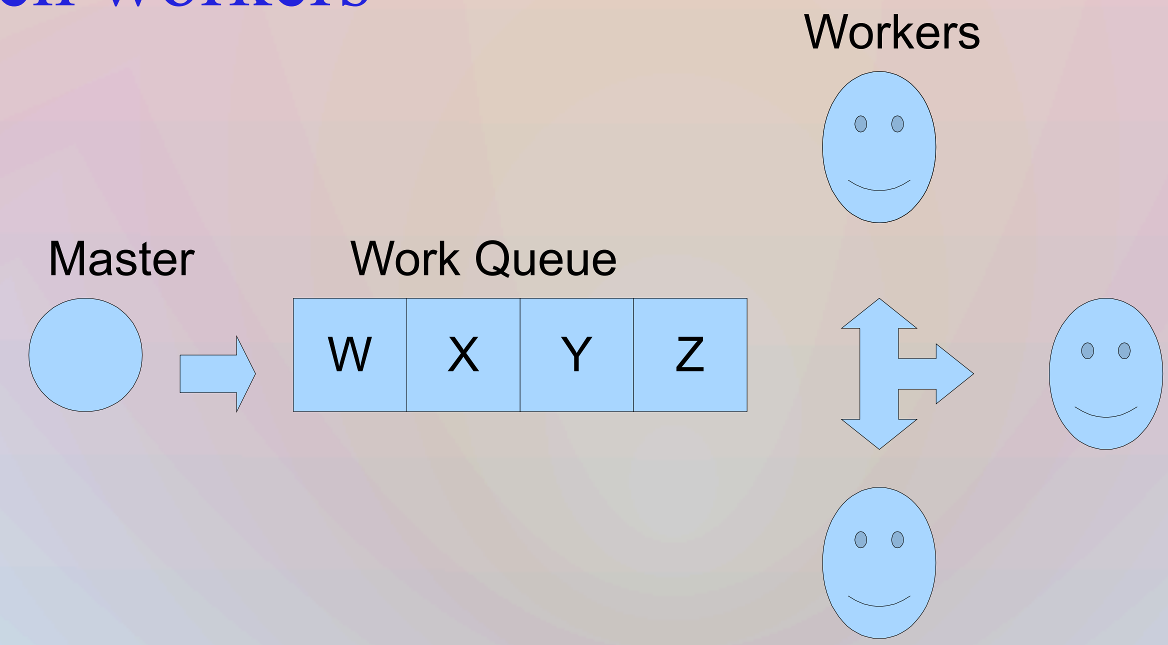
  = Fibonacci (X – 1) + Fibonacci (X - 2);

Workers, Work defined

- In scheduling world,
  - workers are processors,
  - work is threads/processes.
- For these generics in the application domain,
  - workers are tasks
  - work is subprograms
    - or sequential fragments of code that can be wrapped in a subprogram

Work Sharing

- When scheduling new work attempt to give to under-utilized worker.
- Conceptually, a centralized work queue shared between workers



Work Sharing Optimizations used in Parallelism Generics

- Simple Divide and Conquer
- Define work such that;

  Work Item Count = Worker Count

  - i.e., no load-balancing takes place
  - Well suited if load balancing not needed
- Centralized queue ”optimized” out
- Optimal performance for evenly distributed loads

Work Stealing

- Idle workers try to ”steal” work from busy workers.
- Idle worker typically search for work randomly from busy workers.
- Load balancing managed by idle workers.
- Ruled out as an approach for various reasons
  - Work Seeking seen as better choice

Work Sharing Issues

- Pro
  - Optimal for evenly distributed loads, with minimal overhead
- Con
  - Unevenly distributed work can lead to poor processor utilization. (Idle processors waiting for other processors with larger work that could be further broken up)

Work Stealing Issues

- Pro
  - Optimal processor utilization assuming uneven work load distribution.
- Con
  - Compartmentalization structure likely introduces overhead
  - More overhead than work sharing for evenly distributed loads

A Work Stealing Approach (Ruled out)

- Benchmark: Sequential code running on single processor.
- Ideally algorithm should show single worker executes as fast as sequential code.
- An approach with minimal interference on busy workers has idle task suspend busy worker, steal work, then resume worker.
  - Most general purpose OS's don't allow one thread to suspend/resume another.
  - RT OS may allow.

Work Stealing Approaches (Cont)

- Another approach using deques. Idle tasks steal work from the tail of deque, busy workers extract work from the head of deque.
  - Approach used by Cilk++
- Compartmentalizing work to insert on deque introduces overhead to process deque.

Load Balancing Approach Taken: Work Seeking

- Compromise between Work Sharing and Work Stealing models.
- Idle tasks request (seek) work.
- Busy tasks check for existence of work seekers, and offer work.
- Low distributed overhead involves simple check of an atomic Boolean variable
- Direct handoff eliminates need for random seaching for work

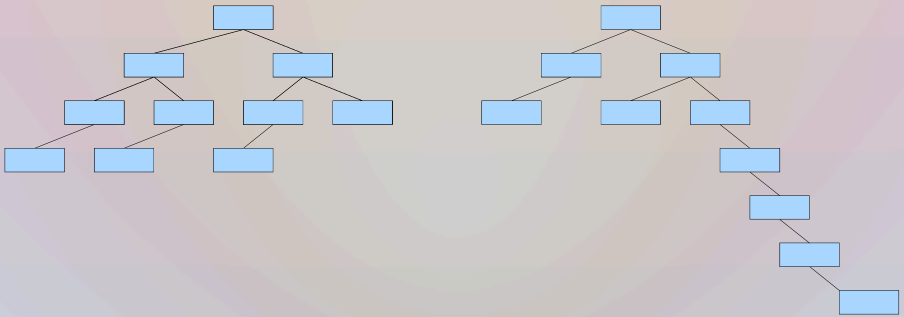
Work Seeking (cont)

- No need to randomly search for busy worker
  - Busy worker hands off work directly to idle worker requesting work.
- Minimal contention, can outperforms barrier approach using POSIX barrier calls.
- Generic implementation does not use heap allocation. Everything is stack based.

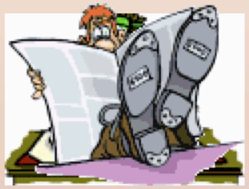
Work Sharing vs Work Seeking

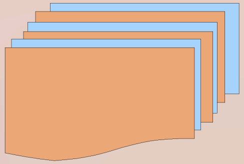
- Choice depends on whether load balancing is needed.

	Evenly distributed loads	Unevenly distributed loads
Work Sharing	Good	Poor processor utilization, high idle times
Work Seeking	Load balancing overhead not needed	Good



Work Seeking





Example Problem: Sum of integers

```
Sum : Integer := 0;
for I in 1 .. 1_000_000_000 loop
  Sum := Sum + I;
end loop
```

- Divide and Conquor between available processors.
- Assuming two processors mapped to two tasks,
  - T1 gets 1 .. 500_000_000
  - T2 gets 500_000_001 .. 1_000_000_000
- Issue: Race condition updating Sum
- Each task gets own copy of global Sum
  - Final result involves reducing copies of Sum

Sum of Integers: (cont)

- Generally, we can add parallelism to process globals if reducing operation is associative.
  - e.g. Addition, Appending to list, Min/Max, multiplication?
- Order of operations is preserved.
  - e.g. Appending integers to list results in sorted list from 1 .. 1_000_000_000,
  - same result as sequential code

Sum of integers (cont)

```
task type Worker is
  entry Initialize (Start_Index, Finish_Index : Integer);
  entry Total (Result : out Integer);
end Worker;
task body Worker is
  Start, Finish : Integer;
  Sum : Integer := 0;
begin
  accept Initialize (Start_Index, Finish_Index : Integer) do
    Start := Start_Index;
    Finish := Finish_Index;
  end Initialize;

  for I in Start .. Finish loop
    Sum := Sum + I;
  end loop;

  accept Total (Result : out Integer) do
    Result := Sum;
  end Total;
end Worker;

Number_Of_Processors : constant := 2;
Workers : array (1 .. Number_Of_Processors) of Worker;
Results : array (1 .. Number_Of_Processors) of Integer;
Overall_Result : Integer;
begin
  Workers (1).Initialize (1, 500_000_000);
  Workers (2).Initialize (500_000_001, 1_000_000_000);
  Workers (1).Total (Results (1));
  Workers (2).Total (Results (2));
  Overall_Result := Results (1) + Results (2);
```

One can write custom solution in Ada but...

- Too much effort, unless absolutely needed.

(Even worse if generalized for any number of processors).

- More likely to have bugs than simple sequential solution

- Programmers likely wouldn't bother

- Lost Parallelism

Goal

- To facilitate parallelism in loops and recursion.
- Ada's strong nesting shines (Insertion at original loop site).

```
Sum : Integer;
declare
  procedure Iteration (Start, Finish : Positive; Sum : in out Integer) is
  begin
    for I in Start .. Finish loop – Based on original sequential code
      Sum := Sum + I;
    end loop;
  end Iteration;
begin
  Integer_Addition_Reducer  – Work Sharing Generic Instantiation
    (From    => 1,
     To      => 1_000_000_000,
     Process => Iteration'Access,
     Item    => Sum);
end;
```

Work Sharing Generic Instantiation

- Common Reducers may be pre-instantiated and reused/shared

```
with Parallel.Iterate_And_Reduce;
procedure Integer_Addition_Reducer is new
   Parallel.Iterate_And_Reduce
     (Iteration_Index_Type => Positive,
      Element_Type => Integer,
      Reducer => "+",
      Identity_Value => 0);
```

Ultimate Goal

- Even better if we can provide syntactic sugar
- The pragma would expand to the code as shown previously

```
Sum : Integer := 0;
for I in 1 .. 1_000_000_000 loop
   Sum := Sum + I;
end loop
pragma Parallel_Loop   – Idea for a new pragma
  (Load_Balancing => False,  – = Work Sharing, not Work Seeking
   Reducer => ”+”,      – Monoid Reducing function
   Identity => 0,       – Monoid Identity Value
   Result => Sum);      – Global State
```

Work Seeking Version

```
Sum : Integer;
declare
  procedure Iteration
   (Start                : Integer;
    Finish               : in out Integer;
    Others_Seeking_Work      : not null access Parallel.Work_Seeking;
    Sum                  : in out Integer) is
  begin
    for I in Start .. Finish loop       – Based on original sequential code
      Sum := Sum + I;
      if Others_Seeking_Work.all then      – Atomic Boolean check
        Others_Seeking_Work.all := False;  – Stop other workers from checking
        Finish := I;                  – Tell generic how far we got
        exit;                     – Generic will re-invoke us with less work
      end if;
    end loop;
  end Iteration;
begin
  Work_Seeking_Integer_Addition_Reducer    – Pre-instantiated generic
   (From    => 1,
    To      => 1_000_000_000,
    Process => Iteration'Access,
    Item    => Sum);
end;
```

Ultimate Work Seeking Version

- Note almost identical to work sharing version

```
Sum : Integer := 0;
for I in 1 .. 1_000_000_000 loop
   Sum := Sum + I;
end loop

pragma Parallel_Loop   – Idea for a new pragma
  (Load_Balancing => True,  – Work Seeking, not Work Sharing
   Reducer => "+",      – Monoid Reducing function
   Identity => 0,      – Monoid Identity Value
   Result => Sum);     – Global State
```

Parallel Recursion

- Idea is to allow workers to recurse independently of each other.
  - While one worker is recursing upwards, others may still be recursing down the tree.
- Unlike loop iteration, total iteration count not typically known.
- Number of ”splits” at given node likely is known however.

Possible Recursion Syntax Example

- Similarly for parallel recursion...

```
procedure Iterate (Container : Tree;
                   Process   : not null access procedure (Position : Cursor))
is
    procedure Span_Tree (Node : Node_Access) is
    begin
        if Node = null then
           return;
        end if;

        Span_Tree (Node.Left);
        Process (Cursor'(Container'Unrestricted_Access, Node));
        Span_Tree (Node.Right);
    end Span_Tree;
    pragma Parallel_Procedure (Load_Balancing => True, Splits => 2);
begin  – Iterate
   Span_Tree (Container.Root);
end Iterate;
```

Lessons Learned: Affinity

- Affinity: locking tasks to specific processors
- Thought extra control would improve performance
- Seldom provided benefit, and only if;

    iterations mod processors = 0

  or

    processor count insignifcant compared to iteration count

- Otherwise, better left to scheduler to decide
  - Could consider sophisticated dynamic algorithm

Affinity

- Assume 2 processors, 3 iterations
- With workers = 2. W1 <= I1 W2 <= I2-I3
  - W1 Finishes I1 when W2 starts I3
    - Total time = 2 * Iteration time
    - Idle time = 1 * iterator time
- With workers = 3. p1 <= W1, p2 <= W2-W3
  - P1 finishes W1 when p2 is half-way through W2 & W3
    - Total time = (1 + (0.5 + 0.5)) Iteration time
    - Idle time = 1 * iterator time

Without Affinity

- 3 workers, 3 iterations
- OS scheduler migrates workers between processors as needed to provide fair sharing of processors
- All 3 workers complete at the same time.
  - Total time = 3 * iteration time / processor count
  - Idle time = 0
  - 1.5t beats 2t

Lessons Learned: Choosing Worker Count

- If iterations count significant relative to processor count...
  - If iteration count >= processor count

    Select worker count that is the smallest factor of the iteration count that is greater or equal to the number of processors
  - else

    Use Iteration count
- else use processor count

Iterative Worker Count Example

- e.g. for 4 processor target

Iteration Count	Recommended Worker Count
3	3
4	4
5	5
6	6
7	7
8	4
9	9
10	5
11	11
12	4

Work Budget

- Number of times a worker task may seek work
  - 1 approximates work sharing
  - -1 (unlimited)
- Thought diminishing returns would mean need to tune value for optimum performance
- Generally found that unlimited work budget provides optimum results for work seeking.

Subcontractor count

- For recursion, since iteration count is unknown
- = Number of sub workers (subcontractors) a worker is allowed to ”hire”
- Used for initial loading of workers.
- Attempts to evenly distribute workers among available processors. Better to assign as soon as possible in the recursion

Possibility for industrial usage Battlefield Spectrum Management

- Algorithm to assign radio frequencies to emitters.
- Used by signal planners in military to plan communications deployment
- Limited Frequencies
- Interference
- Numerical analysis can take time
- Looping through emitters suggest these generics could improve performance.

To Do

- Port to RTOS
  - MaRTE specifically
  - Add work stealing generics with suspend/resume semantics
  - Compare work stealing against work seeking, work sharing.
- Follow up on interest for syntactic sugar
  - AI for post Ada 2012?

Performance Results

- Single worker performs comparably to sequential code
- Ada generics significantly outperform similar examples written in Cilk++
- Ada generics significantly outperform non-generic Ada code using POSIX barriers to manage splits and joins for matrix solving, partial diff. equations.

Conclusions

- Parallel Generics encourage increased use of parallelism in applications.
- Further simplification possible
  - Syntactic sugar pragmas
  - Extra compiler checks to validate parallel usage
- Default affinity may be good enough here
- Programmer needs to indicate preference for load balancing. Compiler likely can't make decision.

Questions?