Modern parallelism models

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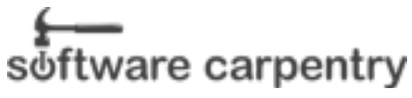

Agenda

- PGAS
- Cilk
- TBB
- Dataflow

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PGAS

Partitioned global address space:

- Unified Parallel C, SHMEM
- Coarray Fortran
- Fortress
- Chapel
- X10
- Global Arrays
- ZPL

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PGAS: OpenSHMEM

```c
#include <shmem.h>

long pSync[_SHMEM_BARRIER_SYNC_SIZE]; /* Symmetric work array */
int number;                           /* Symmetric data */

int main(){
    start_pes(0);                     /* Initialize the OpenSHMEM library */
    int npes = num_pes();             /* Get the number of PEs */
    int me = my_pe ();                /* Get the rank of the PE */

    if(me == 0){
        shmem_int_put(&number, &number, 1, 1);
        shmem_quiet();
    }
    shmem_barrier(0,0,2,pSync);
    if(me == 1) printf("PE 1 received number %d from PE 0\n", number);

    shmem_barrier_all();              /* Synchronize */
    return (0);
}
```

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PGAS: UPC

Example: adding two vectors

```upc
#include <upc_relaxed.h>
#define N 100*THREADS

shared int v1[N], v2[N], v1plusv2[N];

int main(){
    for(int i = MYTHREAD; i < N; i += THREADS) v1plusv2[i]=v1[i]+v2[i];
    // upc_forall(i = 0; i < N; i++; i) v1plusv2[i]=v1[i]+v2[i];
    return 0;
}
```

Example: matrix-vector multiplication

```upc
#include <upc_relaxed.h>

shared [THREADS] int a[THREADS][THREADS];
shared int b[THREADS], c[THREADS];

int main(){
    int i, j;
    upc_forall(i = 0; i < THREADS; i++; i){
        c[i] = 0;
        for(j = 0; j < THREADS; j++)
            c[i] += a[i][j]*b[j];
    }
    return 0;
}
```

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PGAS: Chapel

Example: tree traversal

```
 1 config const treeHeight: uint = 4;
 2
 3 class node {
 4   var id: int;
 5   var left, right: node;
 6   proc ~node() {
 7     if left then delete left;
 8     if right then delete right;
 9   }
10 }
11
12 proc buildTree(height: uint = treeHeight, id: int = 1): node {
13   var newNode = new node(id);
14
15   if height > 1 {
16     cobegin {
17       newNode.left  = buildTree(height-1, id + 1);
18       newNode.right = buildTree(height-1, id + (1 << (height-1)));
19     }
20   }
21   return newNode;
22 }
23
24 proc sum(n: node): int {
25   var total = n.id;
26
27   if n.left != nil {
28     var sumLeft, sumRight: int;
29     cobegin ref(sumLeft, sumRight) {
30       sumLeft = sum(n.left);
31       sumRight = sum(n.right);
32     }
33     total += (sumLeft + sumRight);
34   }
35   return total;
36 }
37
38 proc main() {
39   var root = buildTree();
40   writeln("sum=", sum(root));
41   delete root;
42 }
```

Example: distributed linked list

```
 1 class Node {
 2   var data: real;
 3   var next: Node;
 4 }
 5
 6 var head = new Node(0);
 7 var current = head;
 8 for i in 1..numLocales-1 do
 9   on Locales[i] {
10     current.next = new Node(i);
11     current = current.next;
12   }
13
14 current = head;
15 while current {
16   on current {
17     writeln("node with data = ", current.data, " on locale ", here.id);
18     current = current.next;
19   }
20 }
```

Task Parallelism:

```
cobegin { task1(); task2(); }
coforall i in aggregate do task(i);
sync { begin task1(); begin task2(); }
```

Data Parallelism:

```
forall a in A do a = 1.0;
[a in A] a = 1.0;
A = 1.0;
```

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Intel Cilk Plus

Task-based parallelism in three keywords:

- cilk_for
- cilk_spawn
- cilk_sync

```
~/Dropbox/sandbox $ module load gcc/4.9.0
~/Dropbox/sandbox $ g++ cilk.cpp -fcilkplus
~/Dropbox/sandbox $ icpc cilk.cpp
~/Dropbox/sandbox $
~/Dropbox/sandbox $ CILK_NWORKERS=12 ./a.out
```

Example: matrix-vector multiplication

```
      ...
18    cilk_for(int i = 0; i < N; i++)
19    for(int j = 0; j < N; j++)
20    c[i] += a[i+j*N]*b[j];
      ...
```

Example: the Fibonacci numbers

```
 1 #include <stdio.h>
 2 #include <cilk/cilk.h>
 3
 4 int fib(int n){
 5     if (n < 2) return n;
 6     int x = cilk_spawn fib(n-1);
 7     int y = fib(n-2);
 8     cilk_sync;
 9     return x + y;
10 }
11
12 int main(){
13     printf("%d\n", fib(40));
14     return 0;
15 }
```

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Extensions for Array Notations Programming Model:

section_operator ::=
[<lower bound>:<length>:<stride>]

Example: vectorisation (saxpy)

```
1 #include <cilk/cilk.h>
2 #include <stdio.h>
3 #include <algorithm>
4
5 void saxpy_vec(int m, float a, float x[m], float y[m]){
6     y[:] += a*x[:];
7 }
8
9 int main(){
10     float a[2048], b[2048];
11     a[:] = b[:] = std::rand();
12     cilk_for (int i = 0; i < 2048; i +=256){
13         saxpy_vec(256, 2.0, &a[i], &b[i]);
14     }
15     return 0;
16 }
```

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Intel Threading Building Blocks

- Algorithms — tbb::parallel_for, tbb::parallel_reduce, tbb::parallel_sort
- Containers — tbb::concurrent_vector
- Allocators — tbb::cache_aligned_allocator, tbb::scalable_allocator
- Atomics — tbb::fetch_and_add, tbb::compare_and_swap
- Mutexes — tbb::mutex, tbb::spin_mutex

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Intel Threading Building Blocks

Example: finding average + reduction

```
1 #include "tbb/parallel_for.h"
2 #include "tbb/parallel_reduce.h"
3 #include "tbb/blocked_range.h"
4 #include <algorithm>
5 #include <iostream>
6 #define N 5000
7
8 void average(float* in, float* out, int size){
9     static tbb::affinity_partitioner p;
10    tbb::parallel_for( tbb::blocked_range<int>( 1, N ), [&](const tbb::blocked_range<int>& range){
11        for(int i = range.begin(); i != range.end(); ++i)
12        out[i] = (in[i-1]+in[i]+in[i+1])*(1/3.f);
13    }, p);
14 }
15
16 float sum(float* array, size_t n){
17    return tbb::parallel_reduce( tbb::blocked_range<float*>( array, array+n ), 0.f,
18                                 [](const tbb::blocked_range<float*>& r, float value) -> float {
19                                     return std::accumulate(r.begin(),r.end(),value);
20                                 }, std::plus<float>());
21 }
22
23 int main(){
24    float out[N];  out[:] = 0.;
25    float in[N+1]; in[:] = 2.;
26    average(in, out, N);
27    std::cout << "Total: " << sum(out,N) << "\n";
28    return 0;
29 }
```

```
~/Dropbox/sandbox $ icpc tbb.cpp -std=c++11 -ltbb \
                    -I/apps/castor/intel-2013/tbb/include \
                    -L/apps/castor/intel-2013/tbb/lib/intel64
```

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Intel Threading Building Blocks

Example: reduction (alternative)

```
1  #include "tbb/parallel_for.h"
2  #include "tbb/parallel_reduce.h"
3  #include "tbb/blocked_range.h"
4
5  float sum_v2(const float a[], size_t n){
6      class Reduce {
7          public:
8          void operator()( const tbb::blocked_range<size_t>& r ) {
9              sum_l += __sec_reduce_add(part[r.begin():r.size()]);
10         }
11         void join(const Reduce& y){ sum_l += y.sum_l; }
12
13         Reduce(Reduce& x, tbb::split) : part(x.part), sum_l(0) {}
14         Reduce(const float* a) : part(a), sum_l(0) {}
15     public:
16         float sum_l;
17     private:
18         const float* part;
19     };
20
21     Reduce sf(a);
22     tbb::parallel_reduce( tbb::blocked_range<size_t>(0,n), sf );
23     return sf.sum_l;
24 }
```

Dataflow

- Join-pattern (Join Java, Parallel C#, T++)
- Ambient
- Linda (similar to Charm++/E)
- CAL
- VHDL
- Verilog

Dataflow: Ambient

Example: plus/mul for vector elements

```
1 #include "ambient/ambient.hpp"
2 #include "ambient/container/vector.hpp"
3 #define N 1000
4
5 int main(){
6
7     ambient::vector<int> a(N, 13);
8     ambient::vector<int> b(N, 10);
9     {
10        ambient::actor select(ambient::scope::begin());
11        a += b;
12    }
13    {
14        ambient::actor select(ambient::scope::begin()+1);
15        ambient::async([&](ambient::vector<int>& a, const ambient::vector<int>& b){
16                versioned(a).data[0:get_length(a)] *= versioned(b).data[0:get_length(a)];
17        }, a, b);
18    }
19    ambient::sync();
20    return 0;
21 }
```

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Dataflow: Ambient

Example: Strassen's Matrix Multiplication

```
template<class MatrixA, class MatrixB, class Matrix>
void gemm_strassen(tiles<MatrixA>&& a, tiles<MatrixB>&& b, tiles<Matrix>&& c){
    size_t n  = c.cols/2;
    size_t nt = c.nt/2;
    if(nt){
        tiles<matrix<value_type,allocator_type> > m1(n, n);
        tiles<matrix<value_type,allocator_type> > m2(n, n);
        tiles<matrix<value_type,allocator_type> > m3(n, n);
        tiles<matrix<value_type,allocator_type> > m4(n, n); m4 = a.subset(0, 0, nt, nt);
        tiles<matrix<value_type,allocator_type> > m5(n, n); m5 = b.subset(0, 0, nt, nt);
        tiles<matrix<value_type,allocator_type> > d(n*2, n*2); d = a;
        tiles<matrix<value_type,allocator_type> > e(n*2, n*2); e = b;

        d.subset(0,  0,  nt, nt) += a.subset(0,  nt, nt, nt);  e.subset(0,  0,  nt, nt) += b.subset(0,  nt, nt, nt);
        d.subset(0,  nt, nt, nt) -= a.subset(nt, nt, nt, nt);  e.subset(0,  nt, nt, nt) -= b.subset(nt, nt, nt, nt);
        d.subset(nt, nt, nt, nt) += a.subset(nt, 0,  nt, nt);  e.subset(nt, nt, nt, nt) += b.subset(nt, 0,  nt, nt);
        d.subset(nt, 0,  nt, nt) -= a.subset(0,  0,  nt, nt);  e.subset(nt, 0,  nt, nt) -= b.subset(0,  0,  nt, nt);

        m4 += a.subset(nt, nt, nt, nt);  m5 += b.subset(nt, nt, nt, nt);

        gemm_strassen(d.subset(0,  nt, nt, nt),
                      e.subset(nt, nt, nt, nt),
                      c.subset(0,  0,  nt, nt));
        gemm_strassen(a.subset(0,  0,  nt, nt),
                      e.subset(0,  nt, nt, nt),
                      c.subset(0,  nt, nt, nt));
        gemm_strassen(d.subset(nt, nt, nt, nt),
                      b.subset(0,  0,  nt, nt),
                      c.subset(nt, 0,  nt, nt));
        gemm_strassen(d.subset(nt, 0,  nt, nt),
                      e.subset(0,  0,  nt, nt),
                      c.subset(nt, nt, nt, nt));

        gemm_strassen(std::move(m4), std::move(m5),
                      std::move(m1));
        gemm_strassen(d.subset(0,  0,  nt, nt),
                      b.subset(nt, nt, nt, nt),
                      std::move(m2));
        gemm_strassen(a.subset(nt, nt, nt, nt),
                      e.subset(nt, 0,  nt, nt),
                      std::move(m3));

        c.subset(nt, nt, nt, nt) += c.subset(0,  nt, nt, nt);
        c.subset(nt, nt, nt, nt) -= c.subset(nt, 0,  nt, nt);

        c.subset(0,  0,  nt, nt) += m1;
        c.subset(nt, nt, nt, nt) += m1;
        c.subset(0,  nt, nt, nt) += m2;
        c.subset(0,  0,  nt, nt) -= m2;
        c.subset(0,  0,  nt, nt) += m3;
        c.subset(nt, 0,  nt, nt) += m3;
    }else{
        gemm(a[0], b[0], c[0]);
    }
}
```

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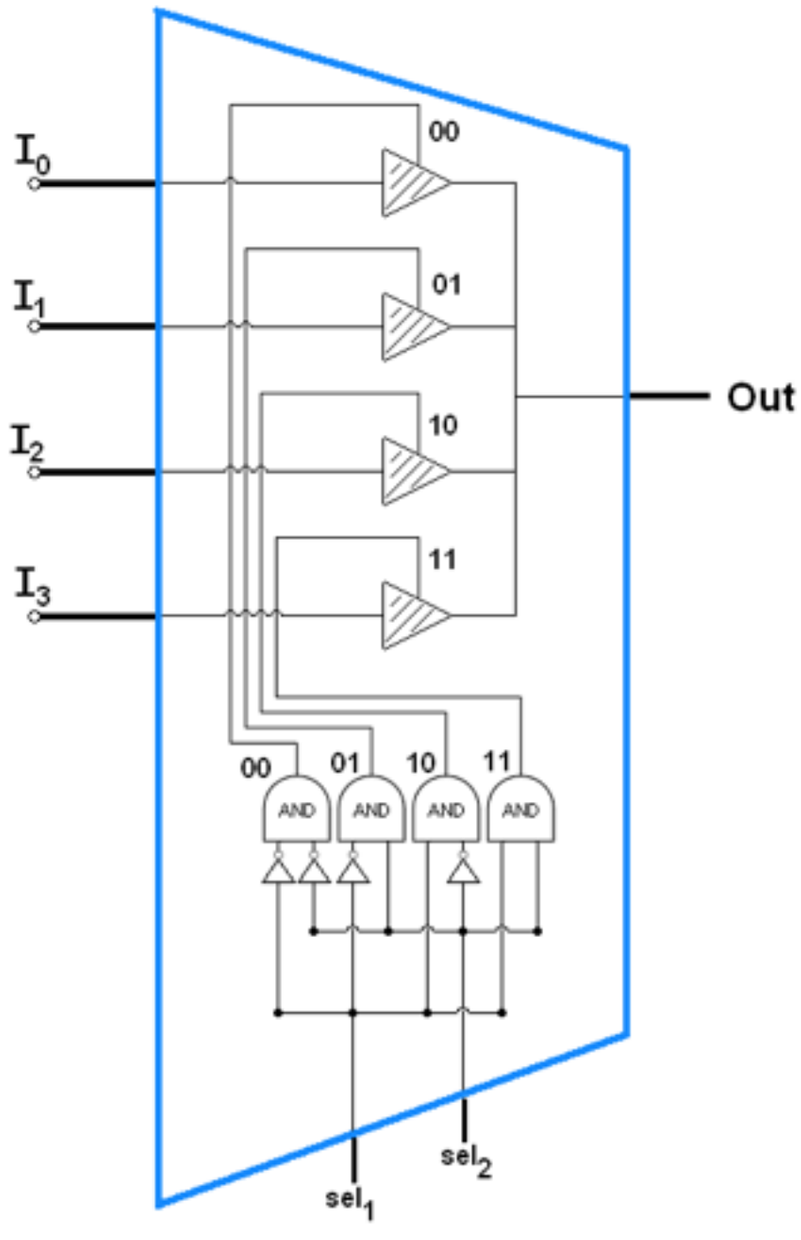
Dataflow: VHDL/Verilog

Example: multiplexer in Verilog

```
1 module mux6( select, d, q );
2
3 input[1:0] select;
4 input[3:0] d;
5 output q;
6
7 reg q;
8 wire[1:0] select;
9 wire[3:0] d;
10
11 always @( select or d)
12 begin
13     q =  ( ~select[0] & ~select[1] & d[0] )
14        | (  select[0] & ~select[1] & d[1] )
15        | ( ~select[0] &  select[1] & d[2] )
16        | (  select[0] &  select[1] & d[3] );
17 end
18
19 endmodule
```



Dataflow: VHDL/Verilog

Example: counter in VHDL

```vhdl
library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.numeric_std.all;    -- for the unsigned type

entity COUNTER is
    generic (
        WIDTH : in natural := 32);
    port (
        RST   : in std_logic;
        CLK   : in std_logic;
        LOAD  : in std_logic;
        DATA  : in std_logic_vector(WIDTH-1 downto 0);
        Q     : out std_logic_vector(WIDTH-1 downto 0));
end entity COUNTER;

architecture RTL of COUNTER is
    signal CNT : unsigned(WIDTH-1 downto 0);
begin
    process(RST, CLK) is
    begin
        if RST = '1' then
            CNT <= (others => '0');
        elsif rising_edge(CLK) then
            if LOAD = '1' then
                CNT <= unsigned(DATA); -- type is converted to unsigned
            else
                CNT <= CNT + 1;
            end if;
        end if;
    end process;

    Q <= std_logic_vector(CNT); -- type is converted back to std_logic_vector
end architecture RTL;
```

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Questions

End of the fourth part