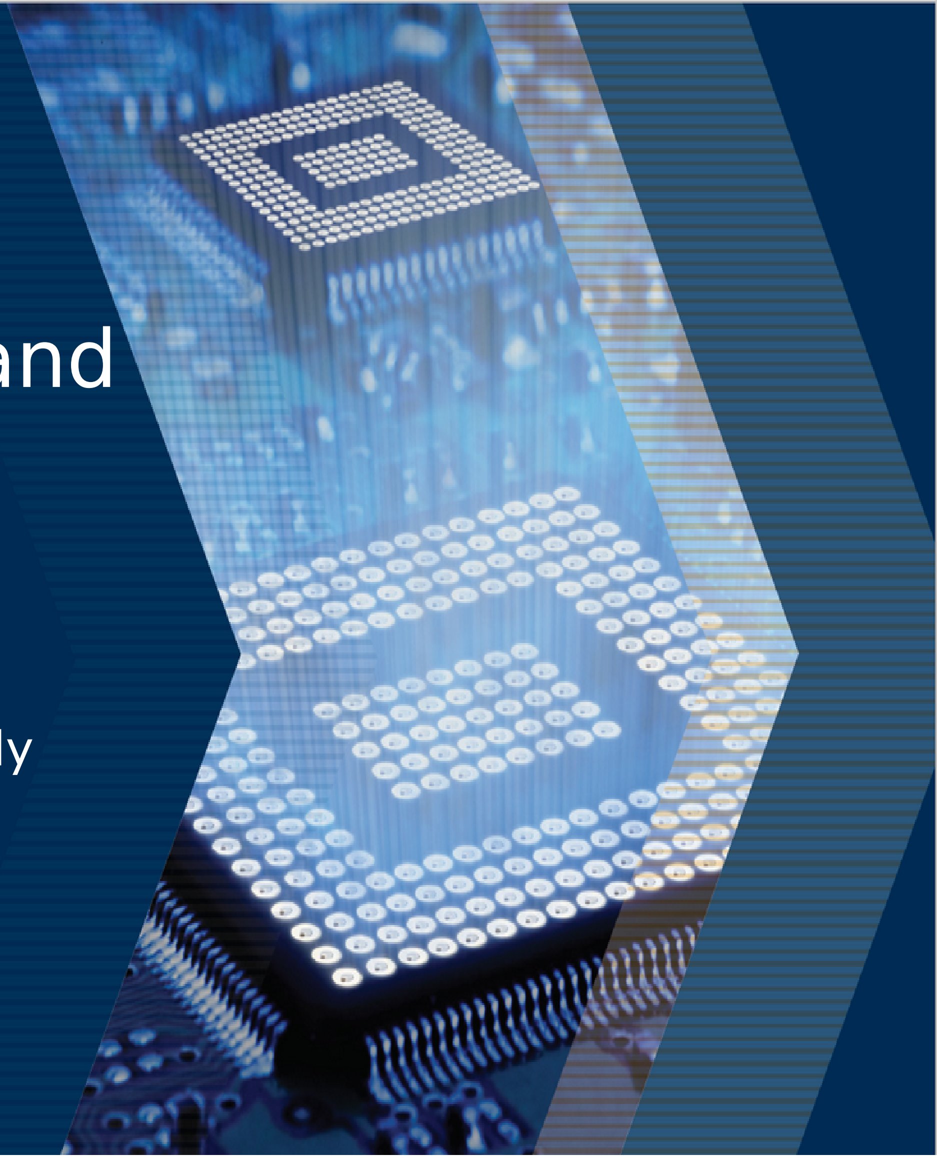
EMU Chick Overview and Hands-On

31 July 2019

Hosted by Will Powell and Jason Riedy

Emu Technology (c) material will be denoted by the use of the Emu logo



CREATING THE NEXT MOORE'S LAW

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Outline

- Introduction to the Emu Chick **(1:30-2:00 PM)**
  - Example 1: Hello World
    - Memory replication
    - Basic thread Spawning Strategies
- Programming for the Chick **(2:00-4:30 PM)**
  - Example 2: STREAM
    - Spawn strategies
    - Granularity
    - Locality awareness
  - Example 3: Sparse Matrix Vector Multiply (SpMV)
    - COO for fully interleaved operation
    - CSR decomposition for the Chick

Emu Chick Overview

Emu Innovation Overview

Designed from the ground up to deal with applications that exhibit little locality

- Massive Shared Memory for in-Memory Computing
  - No I/O bottlenecks
- **EMU** moves ("***Migrates***") the program context to the locale of the data accessed
  - Lower energy – less data moved shorter distances
- Finely Grained Parallelism
  - Reduces concurrency limits
- Compute, memory size, memory bandwidth and software scale simultaneously

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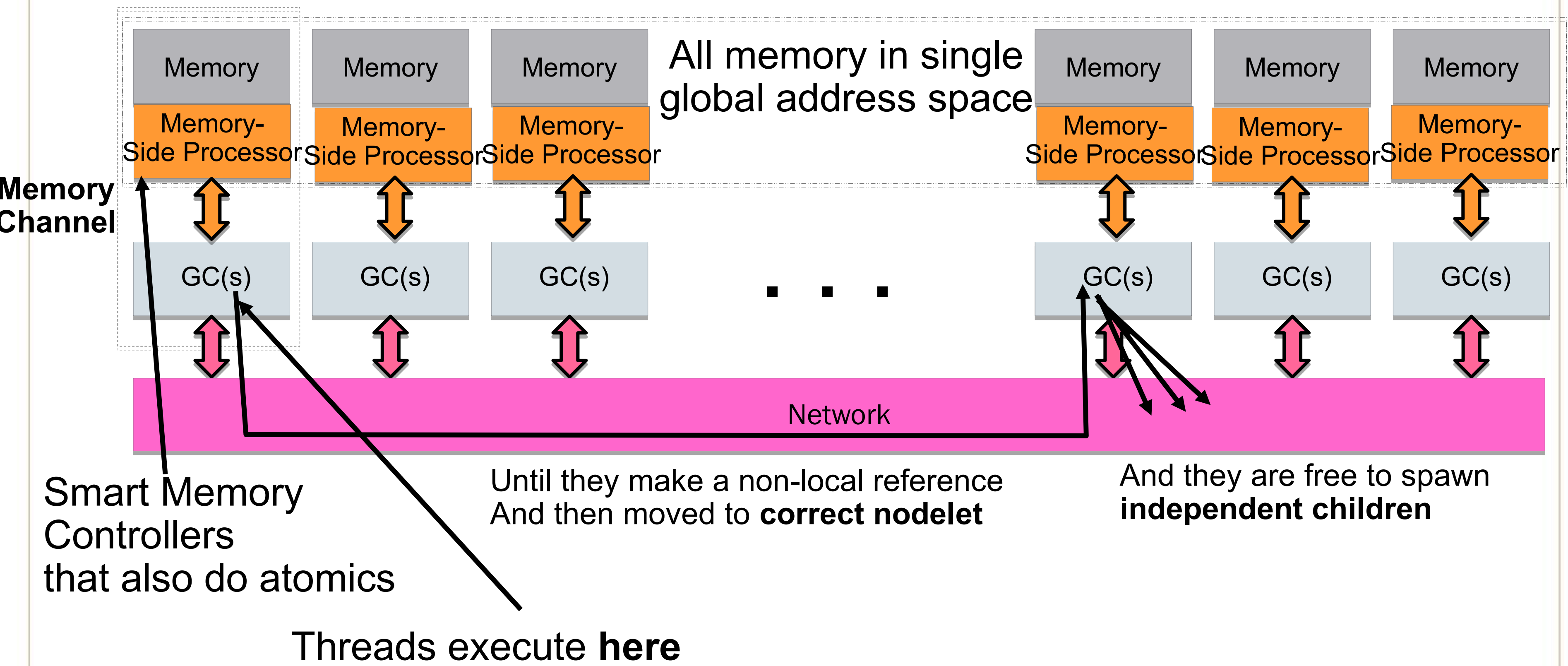
Emu Architecture Functional Diagram

Nodelet: New unit of parallelism



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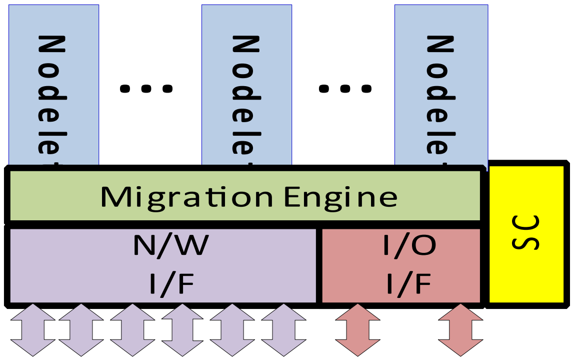
Node Architecture

- 8 Nodelets
- Migration Engine
- 6 RapidIO 2.3 4-lane network ports
- Stationary Cores (SCs)

  DualCore 64-bit Power E5500
  - 2GB DRAM
  - 1 TB SSD
  - PCIe Gen 3
  - Runs Linux

Stationary Core Runs OS, Launches Jobs



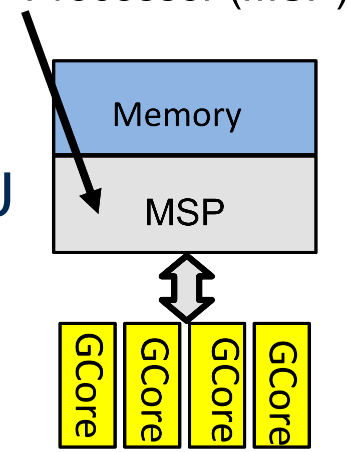
(b) Node

Migrating Threads are major traffic on Network

Nodelet Architecture

- 8 GB DDR4 Narrow Channel Memory
  - Supports 64-bit accesses
- Memory-side Processor (MSP)
  - Handles atomics and remote writes at the memory
- Gossamer Cores (GCs) each with FMA FPU
- Nodelet Queue Manager
  - Run Queue
    - Incoming threads from migrations, spawns, or SC
    - Loaded into vacant execution slots by hardware
  - Migration Queue
    - Threads that need to migrate to non-local data
  - Service Queue
    - Threads that need system services from the SC

Atomics run in Memory-Side Processor (MSP)



(a) Nodelet

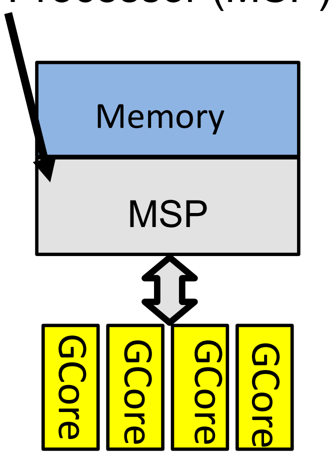
Multi-Threaded Cores

Hardware Thread Management

- Thread scheduling in GCs automatically performed by hardware
- SPAWN instruction
  - Creates new thread and places it in Run Queue
- RELEASE instruction
  - Places thread in Service Queue for processing by SC
- Non-local memory reference causes a migration
  - Thread context packaged by hardware and placed in Migration Queue
  - Migration Engine sends packet to new location and places in Run Queue

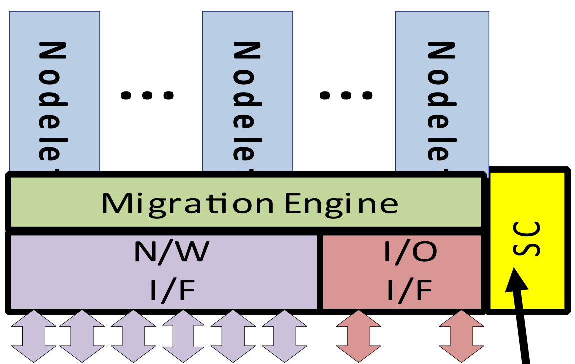
Emu System Hierarchy

Atomics run
in Memory-Side
Processor (MSP)



(a) Nodelet

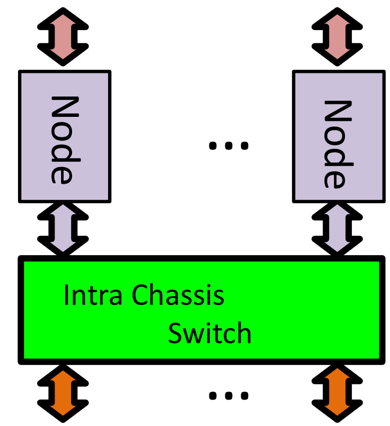
Multi-Threaded Cores



(b) Node

Migrating Threads are major traffic on Network

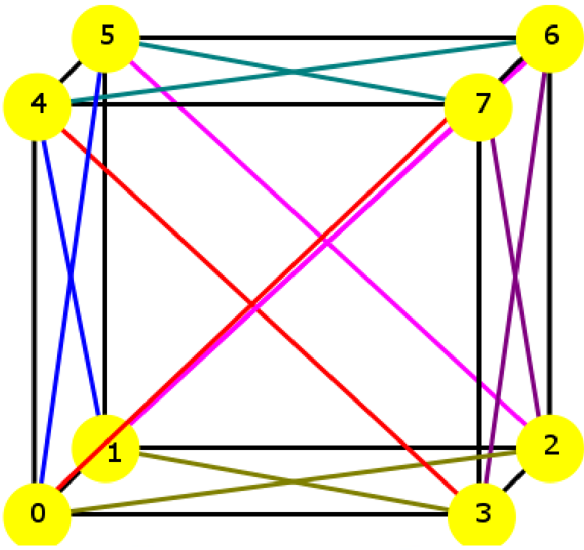
Stationary Core Runs OS, Launches Jobs



Up Links to
(c) Inter-Chassis
Switch

Emu Chick Topology

- System consists of 8 nodes connected in a cube via RapidIO links
  - Each node connects to 6 other nodes
  - Cube edges and face diagonals are connected, but not interior diagonals
- All routes are 2 hops or l
  - 3D diagonals route throug intermediate node
  - All others are 1 hop



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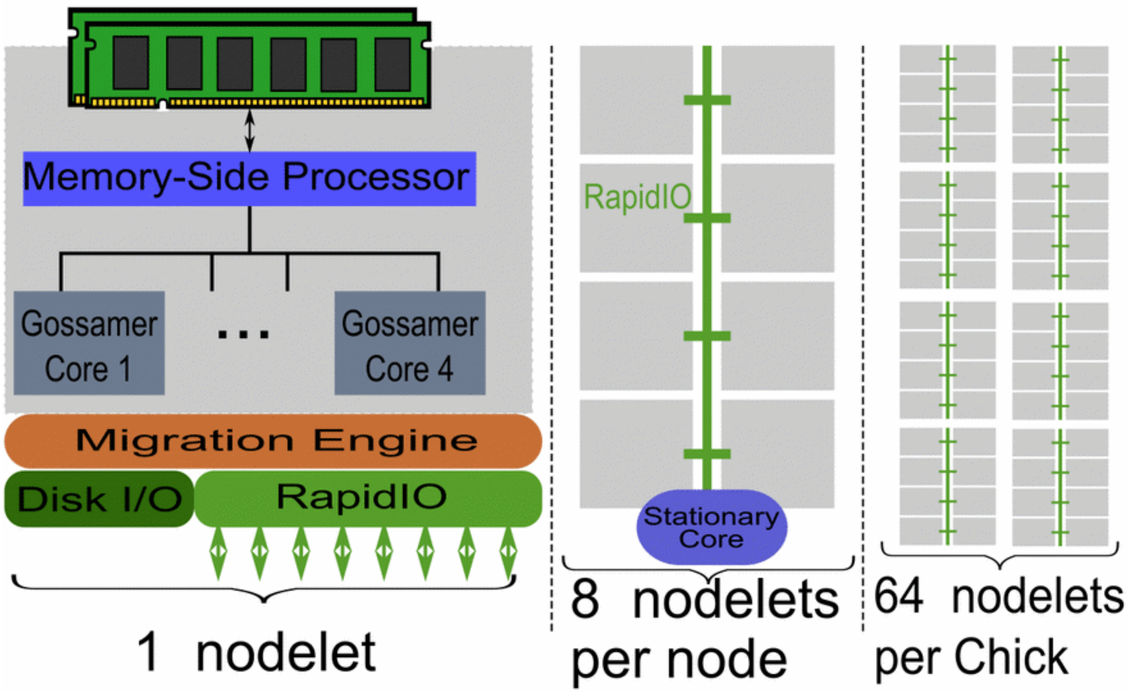
The Current Chick Hardware

- 8 nodes (64 nodelets)
- 512 GB Shared Memory
- 8 TB SSD
- 8192 Concurrent Threads
- Copy room environment
- Shipping now

Emu Chick Architecture



Emu's Migratory Thread Model

Massive, fine-grained multithreading where computation migrates to the data so that accesses are always local

Key Issues:

- Thread control: spawning and synchronization
- Data distribution and affinity of execution
  - Load balance
  - Hotspots
  - Migration patterns

Fine-grained Memory Accesses

- Narrow-channel DRAM (NCDRAM)
  - 8-bit bus allows access at 8-byte granularity without waste
  - Many narrow channels instead of few wide channels
- Remote Writes
  - Write to remote nodelet without migrating
  - Proceed directly to the memory front-end, bypassing the GC
- Remote Atomics
  - Performed in Memory Front-End (MFE), near memory

Emu Programming – Key Features

- **Cilk:** Extensions to C to support thread management
  - cilk_spawn
  - cilk_sync
  - cilk_for
- **Emu Cilk:** Extensions to Cilk to support migrating threads
  - cilk_migrate_hint
  - cilk_spawn_at

Emu Programming – Key Features

- **Memory allocation library:** Specialized malloc/free for data distributed across nodelets
- **Intrinsics:** Allow access to architecture specific operations such as atomic updates

Emu Cilk

Emu hardware dynamically creates and schedules threads

- Normally requires no software intervention
- When a thread completes, it returns values to its parent and dies
- When a thread blocks, it may voluntarily place itself at the back of the run queue (instead of “busy waiting”)
- Number of threads limited only by available memory
- Extremely lightweight – Cilk threads can be very small and still be efficient

Cilk Functions

```
long f = cilk_spawn fib(a, b);
```

- Specifies function may run in parallel with caller
  - Child thread spawned to execute function and parent continues in parallel w/child
  - Otherwise parent executes a standard function call
- Spawn location determines location of
  - Synchronization structure
  - Stack frame (if needed)
- Spawn destination
  - Special functions denote spawn location
  - If no direction is given, then spawn is local

Cilk Functions

`cilk_sync;`

- Current function cannot continue past the `cilk_sync` until all children have completed
- Last thread to reach the `cilk_sync` continues execution – **no waiting**
- Implicit sync at termination of a function

Cilk Functions

```
#pragma cilk grainsize = 4
cilk_for(long i=0; i<SIZE; i++)
  {…}
```

- Divides loop among parallel threads, each containing one or more contiguous loop iterations
- Max number of iterations in each chunk is *grainsize*
- Best for situations where
  - Threads are spawned locally
  - Work per element is fairly uniform

Emu CilkPlus Functions

```
cilk_migrate_hint(p);
```

- Specifies nodelet for next cilk_spawn operation
  - Argument p is a pointer into destination nodelet's memory

```
cilk_spawn_at(p) fib(a,b);
```

- Combines cilk_migrate_hint and cilk_spawn into a macro for single-command spawn
  - Implemented as C macro; may require braces for correct operation

Cilk Fibonacci Example

```
#include "memweb.h"
#include <cilk/cilk.h>
#define N 10
long fib(long n) {
  if (n < 2)
    return n;
  long a = cilk_spawn fib(n-1);
  long b = cilk_spawn fib(n-2);
  cilk_sync;
  return a + b;
}
int main() {
  long result = fib(N);
  printf("fib(%d) = %ld\n", N, result);
}
```

Spawn a thread for each of the `fib()` calls

Wait for threads to complete to ensure `a` and `b` are valid

HELLO WORLD AND HANDS-ON

Ex 1: Emu Hello World

This example demonstrates the following:

- Memory replication
- Basic thread Spawning Strategies

Chick Hands-On Information

- System: **notebook.crnch.gatech.edu**
- Username: pearc$(seq 0 49)
- Login: https://notebook.crnch.gatech.edu

  `Jupyterhub → ephemeral JupyterLab`
- Emu directory: /tools/emu
- Already in $PATH:
  - Compiler: emu-cc [-h]
  - Simulator: emusim.x [-h]

Emusim.x can be used to explore differences in..

- Execution Time
- Migrations
- Memory Map
- Remotes Map
- Run Queue
- Migration Queue
- Remote Queue

Configuration and Summary Statistics

- Generated automatically in `<program>.cdc`
- Check number of threads spawned, their distribution, and number of migrations
- View memory map and remotes map to identify hotspots, poor distribution, and migration patterns

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Examine Simulation Output

- `hello_world.cdc`
  - Execution Time
  - Total Threads
  - Maximum Concurrent Threads
  - Memory Map
  - Remotes Map

Verbose Simulation Statistics

- Generated automatically in `<program>.vsf`
- Identify hotspots/bottlenecks by examining max queue depths
  - Run Queue
  - Migration Queue
  - Remote Queue
- Identify utilization at nodelets
  - IPC (Instructions per cycle: Max 4.0 for 4 cores)
  - Memory Bandwidth (Max 1.0)
  - System IC Bandwidth (Max 1.0)

Examine Simulation Output

- `hello-world.vsf`
  - Much of the same information presented with more detail and different organization
  - Provides queue depths for run queue, migration queue, and remote queue
- Run visualization tool

```
emuvistool hello-world.tqd
```

Ex 1: Exploring Simulation Output

EMU MEMORY ALLOCATION

Memory Allocation

- Replicated, Stack, and Heap sections on each nodelet
- Replicated – global replicated data
- Stack – local memory allocation
  - Thread frames
  - `malloc()/free()`
  - `new()/delete()`
- Heap – distributed memory allocation
  - Specialized `mw_*malloc*()` functions

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Global Replicated Data Structures

```
replicated long c = 3927883;
```

- Instructs compiler to place an instance on each nodelet
- Uses a “View 0” address that always gives local instance
- Must be a **global** variable
- Example Uses:
  - Constants
    - Copy on each nodelet
    - All initialized to the **same** unchanging value
    - EX: PI, pointer to shared data structure
  - Local data
    - Copy on each nodelet
    - May have **differen**t values
    - Use only when it does **not** matter which instance you access!
    - EX: random number table, pointer to local work queue

Dynamic Replicated Pointers

```
long * mw_mallocrepl(size_t blocksize)
```

- Allocates a block on each nodelet, returns replicated pointer
- Similar to using the replicated keyword
- Used when the size of the data structure is not known at compile time

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Replicated Data Structures

- Replicating key shared data structures can improve performance
  - Pointers to shared distributed data e.g. array
  - Copy at each nodelet avoids migrations to get address
  - Compiler generates the address rather than having to pass the address to each function call and carry it during migrations
  - Can reduce spills at function calls

Initializing Replicated Data Structures

```
void mw_replicated_init(long *repl_addr, long value)
```

– Initializes each instance of replicated data structure to value

```
void mw_replicated_init_multiple (long *repl_addr,
         long (*init_func)(long) )
```

– Initializes each instance of replicated data structure using the **result** of the user-defined function `init_func(n)` where `n` is the nodelet number

```
void mw_replicated_init_generic(long *repl_addr,
            void (*init_func)(void *, long) )
```

– Initializes each instance of replicated data structure using the user-defined function `init_func(&obj, n)`, where obj is the address of the ted data structure and n is the nodelet

Accessing Replicated Data Structures

```
void * mw_get_localto(void *r_ptr, void *dest_ptr)
```

– Returns a pointer to the instance of a replicated data structure co-located with the destination pointer

```
void * mw_get_nth(void *r_ptr, unsigned n)
```

– Returns a pointer to the nth instance of a replicated data structure

Local Memory Allocation

- Allocate from the stack on the current nodelet using conventional C/C++ functions
  - malloc and free
  - new and delete

Distributed Memory Allocation

```
void * mw_localmalloc(size_t eltsize, void *ptr)
```

- Block of memory located in same locale as another data structure

```
void * mw_malloc1dlong(unsigned numelements)
```

- Array of longs striped across nodelets round robin

```
void ** mw_malloc2d(unsigned nelements,
                    size_t eltsize)
```

- Array of pointers striped across nodelets round robin
- Each points to a block of memory in the same locale

Distributed Free

```
void mw_free(void *allocedpointer)
```

- Free data allocated by `mw_malloc2d`

```
void mw_localfree(void *allocedpointer)
```

- Free data allocated by `mw_localmalloc`

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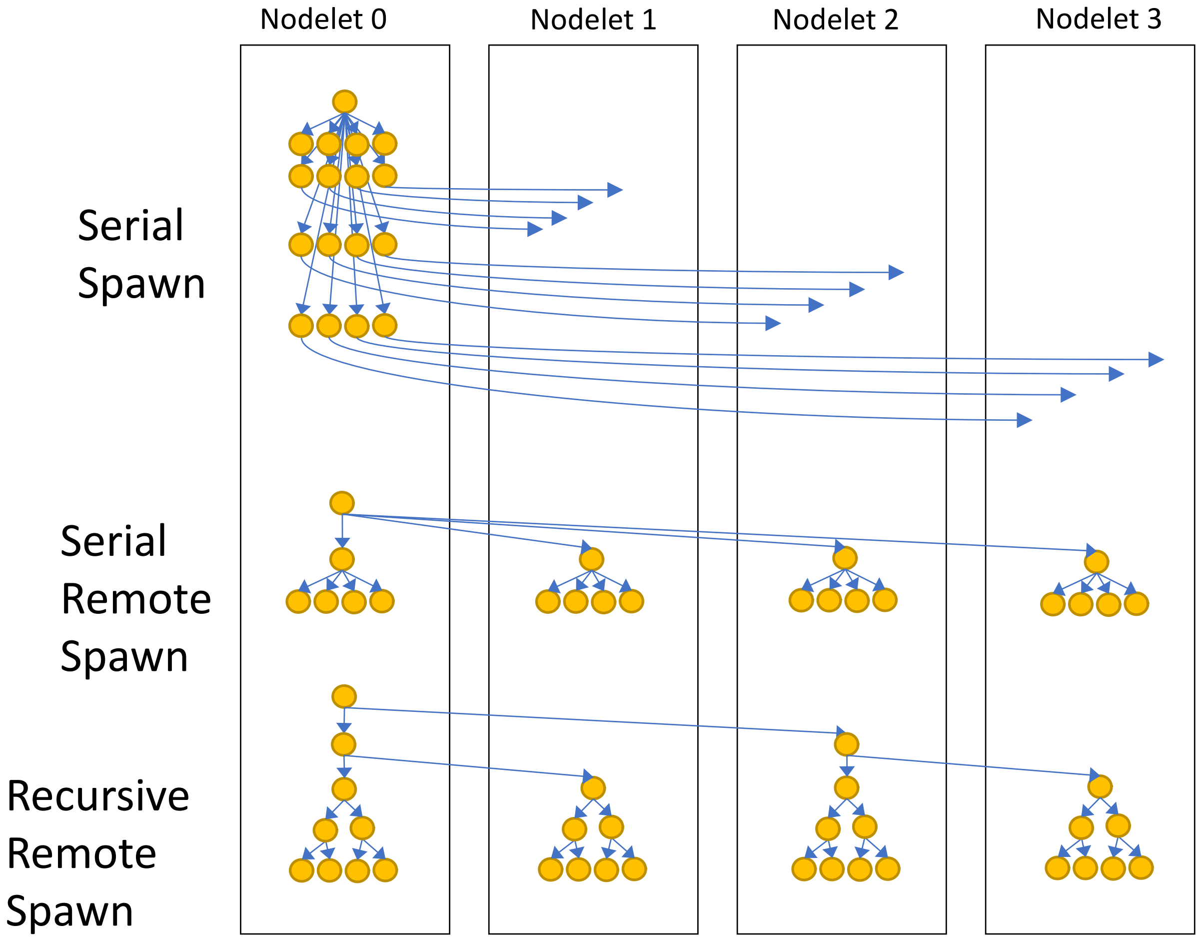
Accessing Distributed Data

```
long * mw_arrayindex(void *array2d,
unsigned long i, unsigned long numblocks,
size_t blocksize)
```

- Inputs:
  - Array allocated with mw_malloc2d
  - Index for first dimension
  - Number of blocks used in malloc2d
  - Blocksize used in malloc2d
- Returns address of array2d[i][0]

Added Spawn Strategies



STREAM Implementation

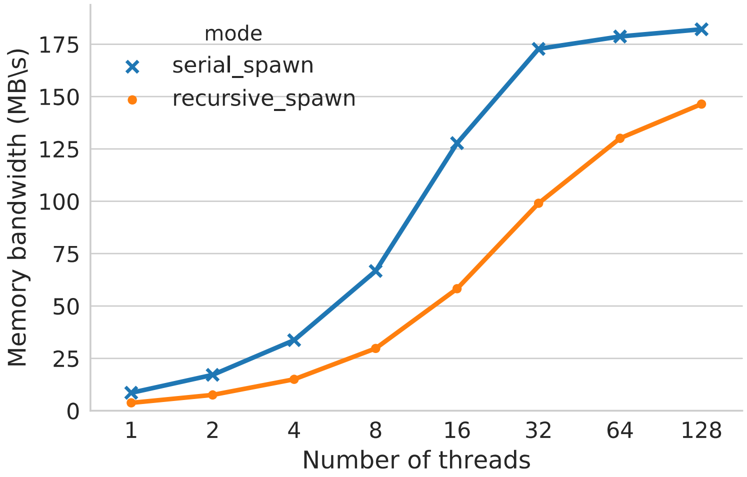
```
// Serial
for (long i = 0; i < n; ++i) {
    c[i] = a[i] + b[i];
}

// Parallel
cilk_for (long i = 0; i < n; ++i) {
    c[i] = a[i] + b[i];
}
```

Ex: 2 Emu STREAM

This example demonstrates the following:

- More complex spawning strategies
- Grain size settings
- Locality awareness (i.e., limiting some migrations)



HARDWARE EXECUTION OVERVIEW

Emu Chick Configuration

- Single-node Execution
  - Program runs on a single node
  - Can access all 8 nodelets but no other nodes
  - Users can work independently on different nodes
- Multi-node Execution
  - Program runs on full system
  - Can access all 8 nodes (64 nodelets)
  - Single user

Emu Chick Hardware Execution

- Compile programs on notebook.crnch.gatech.edu then `scp` to Chick node
- Single-node Execution
  - Launched on node using `emu_handler_and_loader`
- Multi-node Execution
  - Launched on node 0 using `emu_multinode_exec`

Program Execution Utilities

- **Load** program and data to all nodelets
- **Launch** initial thread into the system
- **Monitor** the system exception queue and handle system services until a thread quits or an exception occurs
- **Terminate** by issuing a checkpoint to clear the system and dump any remaining threads
- **Print** information to log files for each thread that quits, exits, generates an exception, or is checkpointed
- **Return** the program’s return value

System Services

- Thread suspends itself and writes thread state registers (TSR) to the system exception queue (SEQ)
- Handler polls system SEQ for threads that need services
- Handler reads the thread from the SEQ and performs the requested service
- Handler then relaunches the thread to nodelet 0

Running Code on the Chick

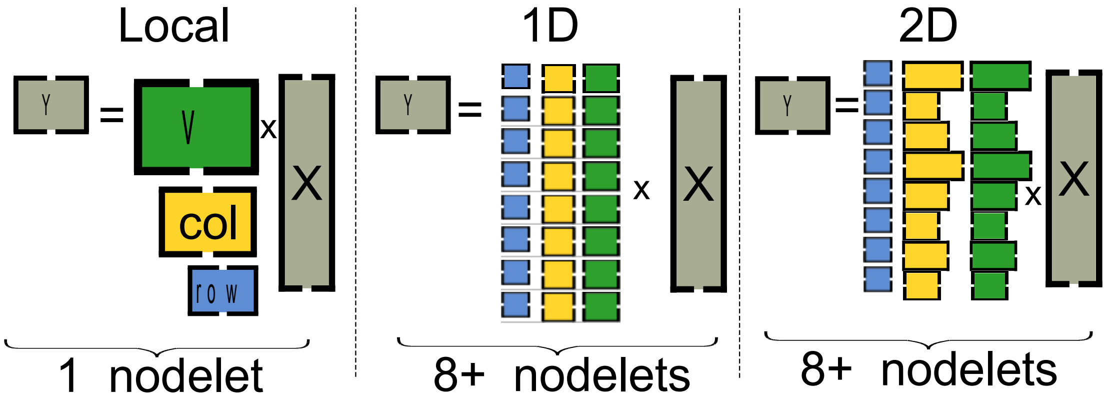
- System: **karrawingi-login.crnch**
  - SSH keys should be set up for you to use
  - ~/.ssh/config includes proxy setup
- Username: pearc$(seq 0 49)
  - *ssh karrawingi-login*
- Emu Chick nodes
  - *ssh n0 – n7*

Ex 3: Emu SpMV

This example demonstrates the following:

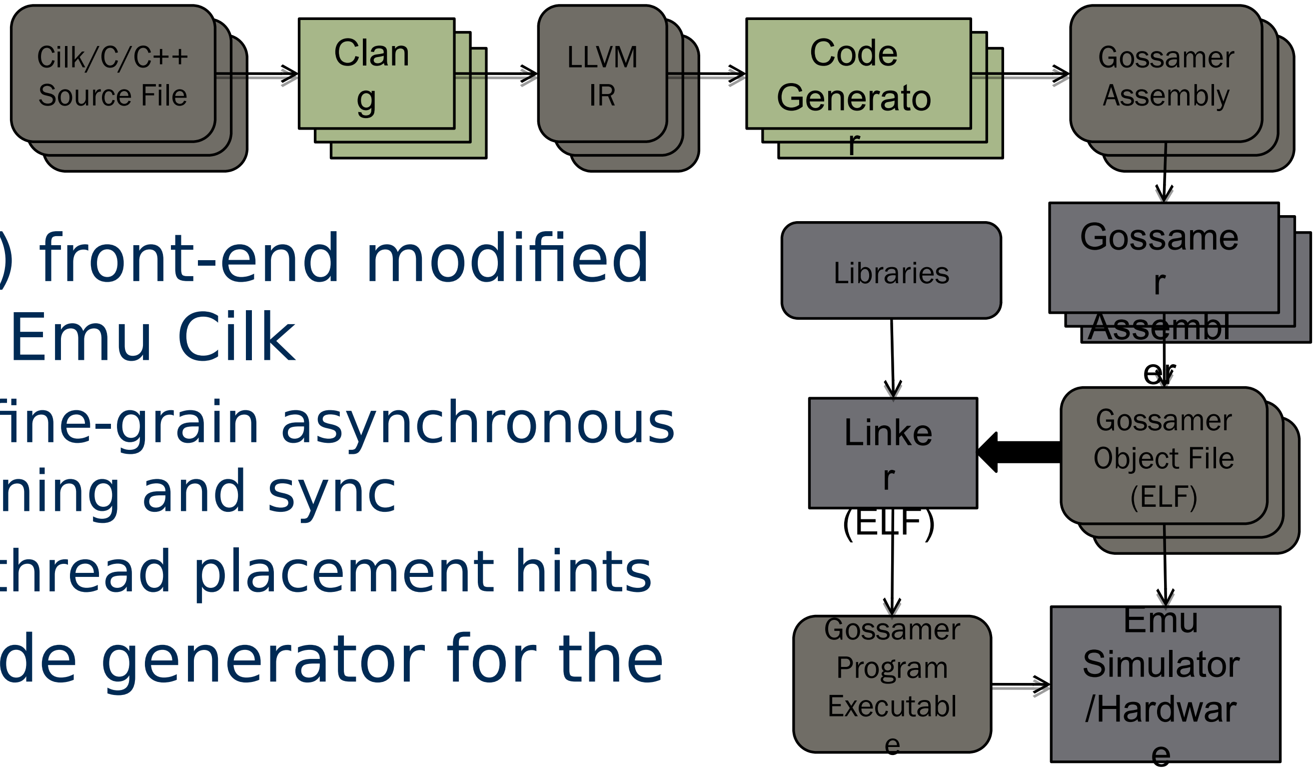
– COO vs CSR layouts

– More advanced data distributions



EMU TOOLCHAINS AND DEVELOPMENT ENVIRONMENT

Emu Cilk Toolchain



- Cilk (clang) front-end modified to support Emu Cilk
  - Supports fine-grain asynchronous task spawning and sync
  - Supports thread placement hints
- Custom code generator for the Emu GCs
- Custom calling convention and run-time support
- Custom assembler and linker

Support for C, C++, and CilkPlus provides **familiar development environment**

CilkPlus Beta Release

- Latest Clang front-end to support
  - C/C++ 2011
  - CilkPlus
- Key CilkPlus features
  - **Reducers:** list, min/max, addition, bitwise AND/OR/XOR, multiplication, ostream, string, vector
  - **Pedigrees:** unique naming convention for threads
- No support for
  - CilkPlus vector operations
- Currently delivered in parallel with standard release

Emu C Utilities

- Set of common patterns for thread-parallel code implemented efficiently as library calls
- Working with local arrays
  - Alternative to cilk_for, no compiler support
- Working with distributed striped arrays
  - 2-level spawn tree, split array for worker functions
- Working with distributed chunked arrays
  - Calculates indices, applies functions to blocked arrays
- Timing hooks
  - Timer subsystem for performance analysis

User Libraries

- GNU Multiple Precision Arithmetic (GMP) Library
  - Library for arbitrary precision arithmetic
  - Currently support integer GMP for Emu
  - Included in current release
- Under development
  - GraphBLAS (UMBC / SEI)
  - OpenMP (Stony Brook University)
- Other efforts
  - STINGER Graph Library (Georgia Tech)
  - Kokkos C++ Ecosystem (Georgia Tech / Sandia)

What have we not covered today?

- Atomics and intrinsics
- Multi-node execution
- Thread management

Backup

Intrinsics

- Set of compiler recognized functions to access architecture specific operations
  - Atomic Arithmetic Operations
  - Remote Arithmetic Operations
  - Other Architecture Specific Operations
  - Thread Management Functions
  - System Queries

Atomic Arithmetic Operations

- Atomic arithmetic operations at the memory

```
long ATOMIC_<INST> (volatile void *A, long D);
  <INST>: ADD/SUB/AND/OR/XOR/MAX/MIN
```

- Four distinct “flavors” of each atomic that specify the value returned and resulting mem

Mnemonic	Return Value	New Memory Value
<op>	Result	Unchanged
<op>S	Result	Orig. D Value
<op>M	Result	Result
<op>MS	Orig. Mem. Value	Result

ATOMIC_ADD Examples

- ATOMIC_ADD(A, D)
  - Reads value at A
  - Adds D
  - Returns result
  - Mem[A] is unchanged
- ATOMIC_ADDS(A, D)
  - Reads value at A
  - Adds D
  - Returns results
  - Mem[A] = D
- ATOMIC_ADDM(A, D)
  - Reads value at A
  - Adds D
  - Returns result
  - Mem[A] = result
- ATOMIC_ADDMS(A, D)
  - Reads value at A
  - Adds D
  - Returns original Mem[A]
  - Mem[A] = result

Remote Arithmetic Operations

```
void REMOTE_<INST>(volatile void *A, long D);
  <INST>: ADD/AND/OR/XOR/MAX/MIN
```

- Significantly reduces migrations by performing atomic updates to memory *without migrating the thread*
- Sends only the data and operation to be performed
  - Consumes less than half the bandwidth of a typical thread migration
- Does not return a value
- Returns an ACK, may be turned off
- Remotes issued by a thread to the same location guaranteed to complete in order

WRD – Remote Write

- Automatically generated by the compiler in place of the store instruction
- Writes the value to remote memory and sends an acknowledgement (ACK)
- If the access is local, treated as a store

FENCE on Remote Update

```
void FENCE();
```

- Used to wait for all remote updates to be acknowledged
- Prevents thread from continuing until all outstanding acknowledgements have been received
- Implicit FENCE before migration, thread suspend, etc.

Swap Operations

```
long ATOMIC_SWAP(volatile void *A, long D)
```

- Replace the contents of memory at `A` with `D`
- Return the original contents of memory at `A`

```
long ATOMIC_CAS(volatile void *A,
  long newVal, long cmpVal)
```

- Compare the contents of memory at `A` to `cmpVal`.
- If they match, swap `newVal` into `A`
- Always return original contents of memory at `A`

Other Operations

```
long POPCNT(long sum, long * ptr)
```

- Counts number of 1s in the word referenced by `ptr`
- Adds this value to `sum` and returns the result

```
unsigned long
  PRIORITY(unsigned long value)
```

- Computes the 6 bit priority encode on `value`
- i.e. bit position of highest numbered non-

Thread Management

`void MIGRATE(volatile void *A)`

- Force a migration to an address

`void RESIZE()`

- Resize the thread to carry only the live registers
- Used by compiler or programmer before a possible migration to reduce thread size

`void RESCHEDULE()`

- Place the thread at the end of the Run Queue to allow a new thread to be scheduled in the core
- Can be used to minimize the impact of busy wait

Thread Management (cont)

- void ENABLE_ACKS() – require acks on remotes
- void DISABLE_ACKS() – turn off acks
- void DISABLE_MIGRATIONS() – cause exception on migration (for debugging)
- void ENABLE_MIGRATIONS() – resume migrations without exceptions
- void DISABLE_INTERRUPTS() – prevent thread from timeslice interupt
- void ENABLE_INTERRUPTS() – allow timeslice interrupts from thread
- void ENTER_CRITICAL_SECTION() – combine DISABLE_MIGRATIONS and DISABLE_INTERRUPTS
- void EXIT_CRITICAL_SECTION() – combine ENABLE_MIGRATIONS and ENABLE_INTERRUPTS

System Query

- CLOCK() - Returns system time on local nodelet (clock ticks)
- THREAD_ID() – Returns the current thread ID
- NODE_ID() – Returns the current Nodelet ID
- NODELETS() - Returns the number of nodelets in the current system
- BYTES_PER_NODELET() – Returns the number of bytes per nodelet
- MAXDEPTH() – maximum spawn depth*

*planned, not yet implemented

Initializing Replicated Data Structures

```
void mw_replicated_init(long *repl_addr, long value)
```

– Initializes each instance of replicated data structure to the same value

```
replicated long N;
int main()
{   …
    long n_elements = compute_n_elements();
    mw_replicated_init(&N, n_elements);
    …
}
```

Initializing Replicated Data Structures

```
void mw_replicated_init_multiple
      (long *repl_addr, long (*init_func)(long))
```

– Initializes each instance of the replicated data structure using the **result** of the user-defined function `init_func(n)` where `n` is the nodelet number

```
replicated long B;
long init_func(long nid) {
   return nid * 5;
}
int main()
{  …
   mw_replicated_init_multiple(&B, init_func);
   …
}
```

Initializing Replicated Data Structures

```
void mw_replicated_init_generic(long *repl_addr,
            void (*init_func)(void *, long) )
```

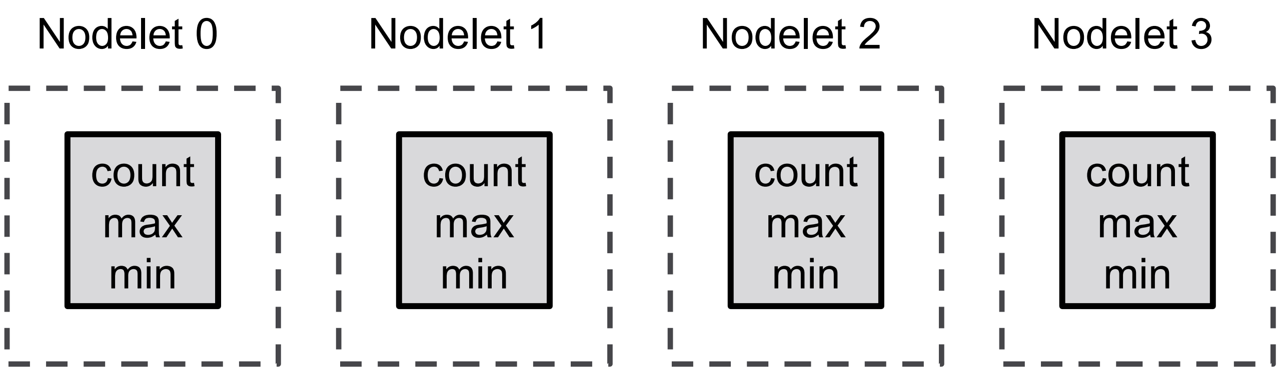
– Initializes each instance of replicated data structure using the user-defined function `init_func(&obj, n)` where `obj` is the address of the replicated data structure and `n` is the nodelet number

```
replicated struct info { long x; long y; } info;
void init_info(void *obj; long nid) {
    struct info *i = (struct info*) obj;
    i->x = node;
    i->y = 5*node + 4;
}
int main()
{   …
    mw_replicated_init_multiple(&info, init_info);
    …
}
```

Allocate Replicated Data Structure

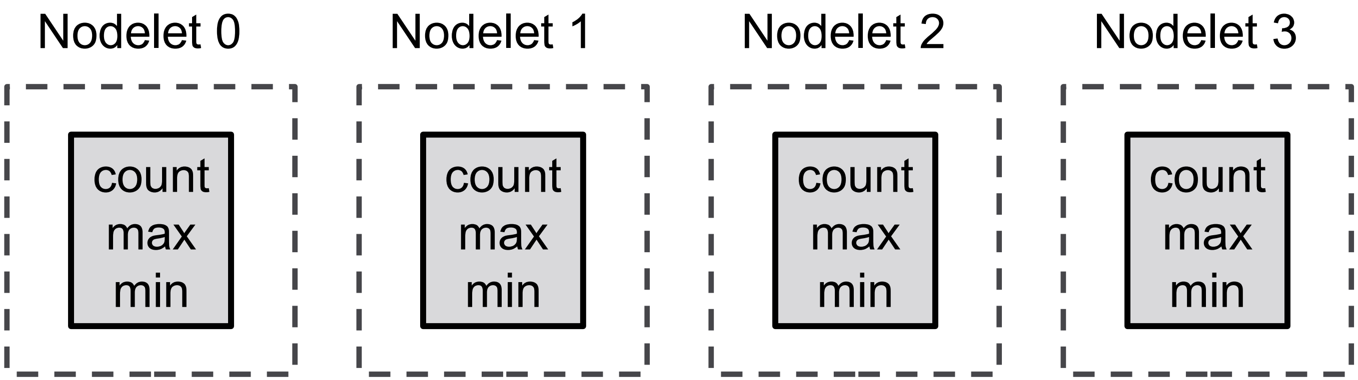
Copy of stats on each nodelet at the same offset

```
struct stats {
    unsigned long count;
    unsigned long max;
    unsigned long min;
};
replicated struct stats s;
```



Initialize Replicated Data Structure

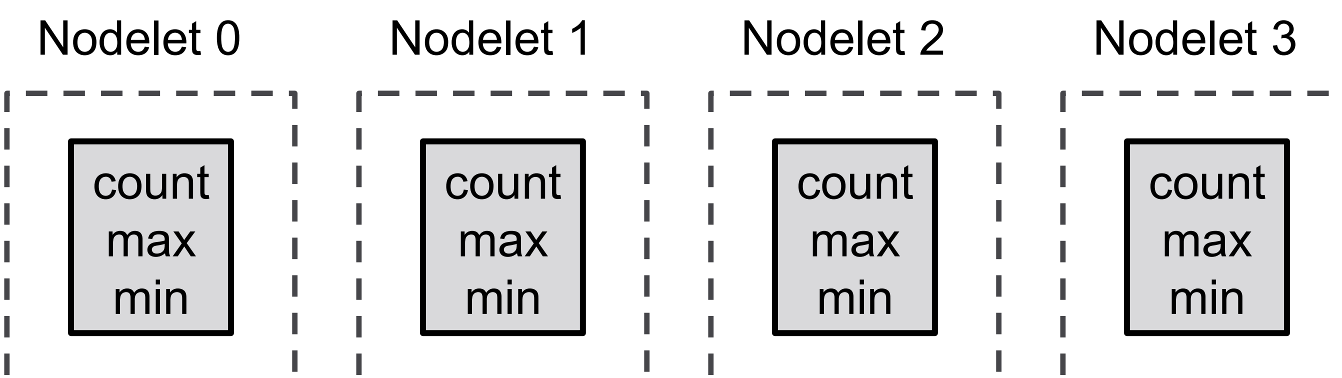
```
// Initialize using mw_get_nth
for (long i=0; i<NODELETS(); i++) {
    struct stats * si = mw_get_nth(&s, i);
    si->count = 0;
    si->max = 0;
    si->min = LONG_MAX;
}
```



Update Replicated Data Structure

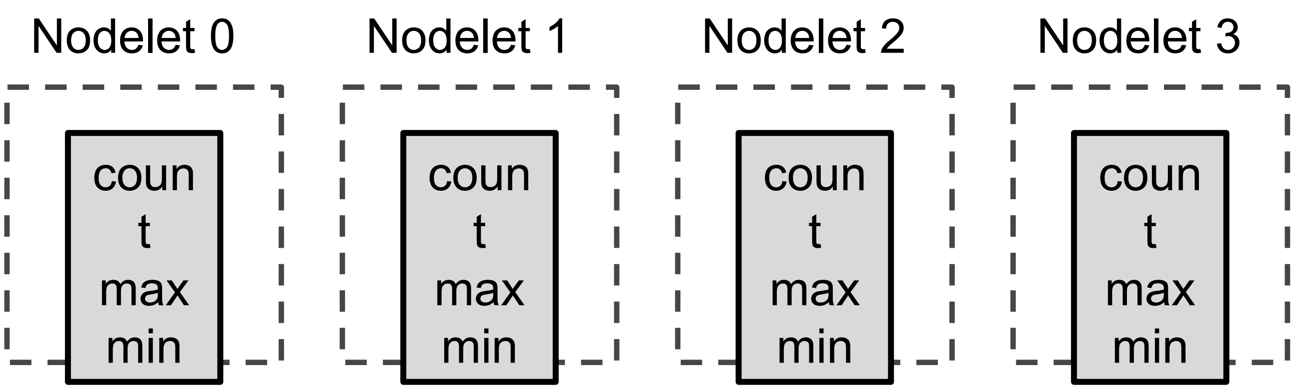
```
// Update stats
cilk_for (long i=0; i<N; i++) {
    unsigned long score = score(A[i]);
    if (score != 0) {
        ATOMIC_ADDM(&(s.count), 1);
        ATOMIC_MAXM(&(s.max), score);
        ATOMIC_MINM(&(s.min), score);
    }
    }
```

Remember to use atomics for shared data



Reduce Replicated Data Structure

```c
// Reduce using mw_get_nth
unsigned long count = 0;
unsigned long max = 0;
unsigned long min = LONG_MAX;
for (long i=0; i<N; i++) {
    struct stats * si = mw_get_nth(&s, i);
    count += si->count;
    if (si->max > max) max = si->max;
    if (si->min < min) min = si->min;
}
```

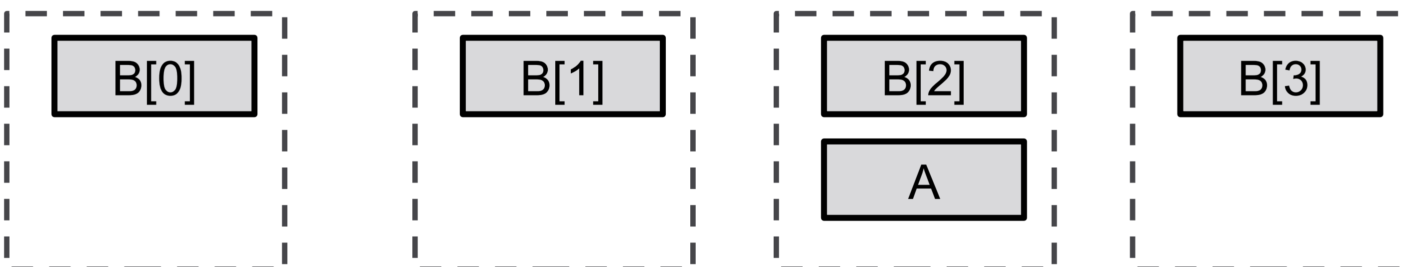


Allocate Co-located Data

```
void * mw_localmalloc(size_t eltsize, void *ptr)
```

- Block of memory of size `eltsize` co-located with address `ptr`
- Accessed using traditional C semantics
- Leaves you at the new location
- Example:

```
long * A = (long *)
        mw_localmalloc(sizeof(long), &B[2]);
```



Allocate 1D Array of Longs

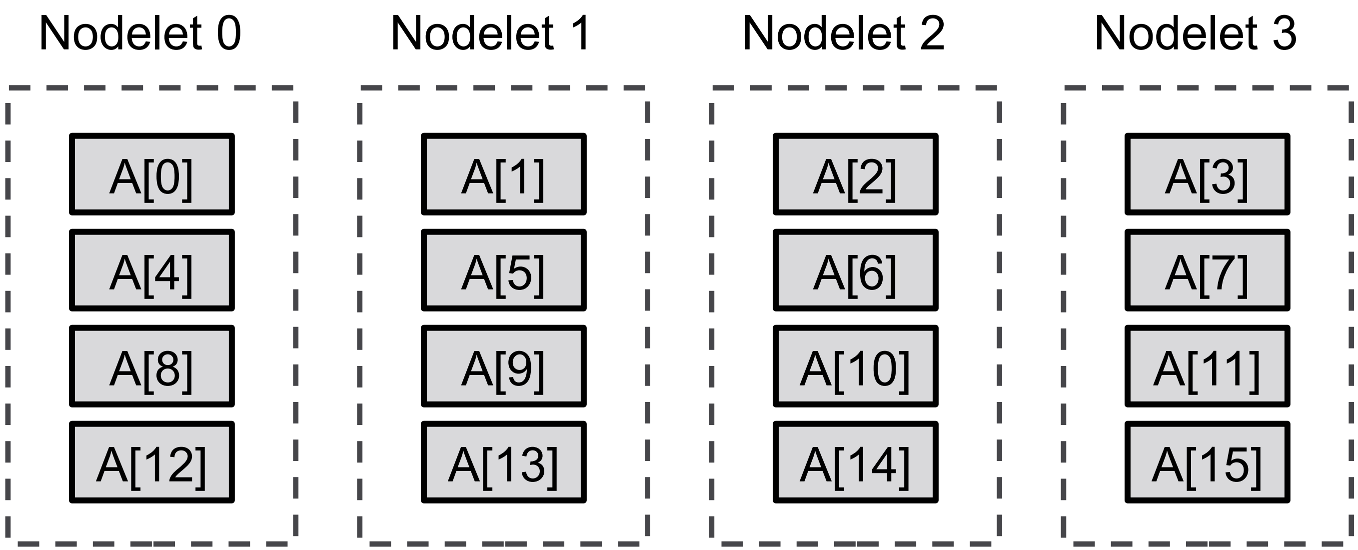
```
long * mw_malloc1dlong(unsigned nelements)
```

- Array of `nelements` longs striped across nodelets round robin
- Accessed using 1D array notation (e.g. A[i])
- ONLY works for 64-bit types (e.g. long)

Example: 1D Array

Array of N elements, striped across nodelets round-robin

```
#define N 16
long * A = (long *) mw_malloc1dlong(N);
for (long i=0; i<N; i++)
    A[i] = i;
```



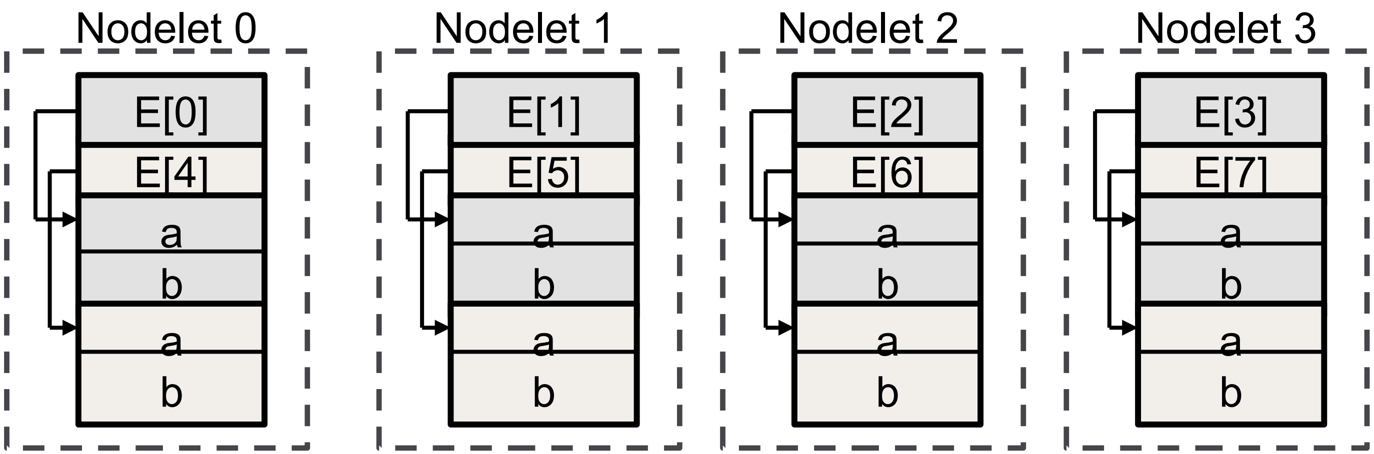
Allocate 2D Array of Elements

```
void ** mw_malloc2d(unsigned nelements,
                    size_t eltsize)
```

- Array of `nelements` pointers striped across nodelets round robin
- Each points to co-located memory block of size `eltsize`
- May be an array of pointers to any type

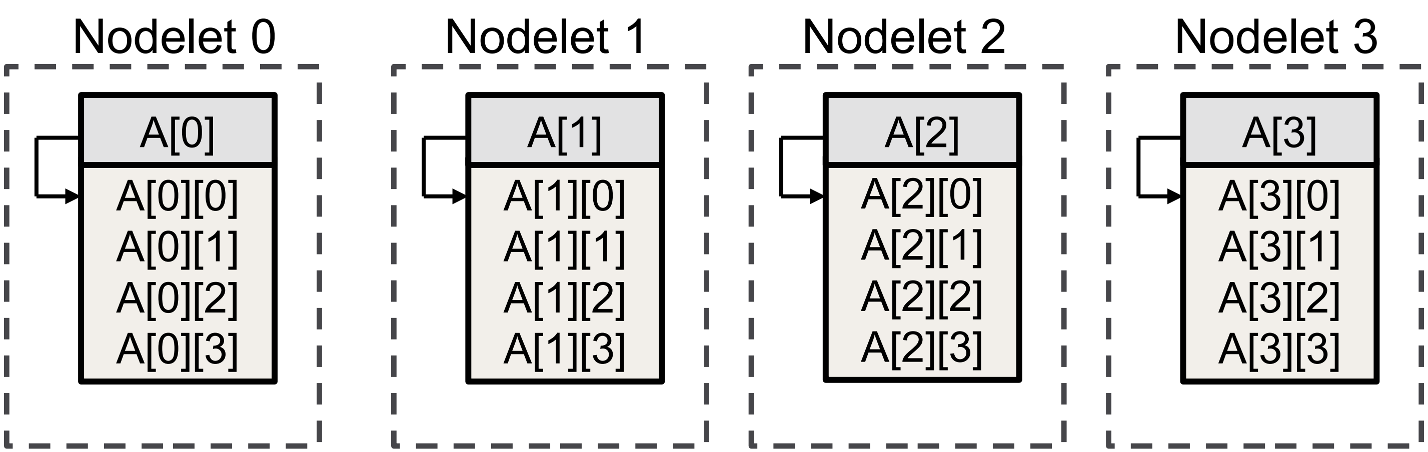
Malloc2d Ex: Array of structs

```
#define N 8
struct element { long a; long b; };
struct element ** E = (struct element **)
    mw_malloc2d(N, sizeof(struct element));
for (long i=0; i<N; i++) {
    E[i]->a = i;
    E[i]->b = 0;
}
```



Malloc2d Ex: Blocked Distribution

```
#define N 16  // # elements in array (power of 2)
long epn = N/NODELETS();  // elements per nodelet
long ** A = (long **)
    mw_malloc2d(NODELETS(), epn * sizeof(long));
for (long i=0; i<N; i++)
    A[i/epn][i%epn] = i;
```



Malloc2d Ex: Wrapped Block Dist.

```
#define N 16
long nBlocks = 8;
long blockSize = N/nBlocks;
long ** A = (long **)
    mw_malloc2d(nBlocks, blockSize * sizeof(long));
for (long i=0; i<N; i++)
    A[i/blockSize][i%blockSize] = i;
```