Modern BSP

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BSP today

- BSP is still the leading model for *distributed* computing, used in industry.
    - MapReduce
    - Pregel
- BSP programming usually done using MPI or the various Apache projects *(Hama, Giraph, Hadoop)*.
- BSPlib provides an accessible way to familiarize yourself with parallel programming.

Google's MapReduce (Example)[1]

- Classic example: word count. The *map* takes (file, content) pair, and emits (word, 1) pairs for each word in the content. The *reduce* function sums over all mapped pairs with the same word.
- The Map and Reduce are performed in parallel, and are both followed by communication and a bulk synchronization, which means MapReduce $\subset$ BSP!

[1]MapReduce: Simplified Data Processing on Large Clusters, Jeffrey Dean and Sanjay Ghemawat (2004)

Google's Pregel

BSP for graph processing, used by Google[2] and Facebook[3]:

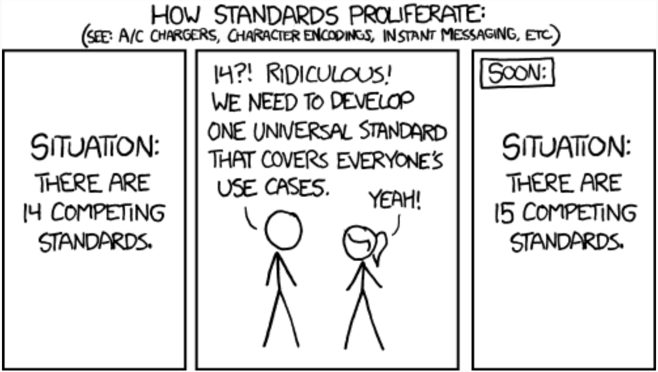
> *"The high-level organization of Pregel programs is inspired by Valiant's Bulk Synchronous Parallel model. Pregel computations consist of a sequence of iterations, called supersteps ... It can read messages sent to V in superstep $S-1$, send messages to other vertices that will be received at superstep $S+1$ ..."*

[2] Pregel: A System for Large-Scale Graph Processing – Malewicz et al. (2010)
[3] One Trillion Edges: Graph Processing at Facebook-Scale - Avery Ching et al (2015).

Modern BSP

- These frameworks are good for big data analytics, too limiting for general purpose scientific computing
- $\implies$ Most scientific software built with MPI
- Modern languages have features (safety, abstractions) which can aid parallel programming. Full power of BSP not yet available in such a language.

Bulk



5th most cited xkcd[4]

[4] https://xkcdref.info/statistics/

Introduction

- **Bulk** is a BSP library for modern C++
- Provides a safe and simple layer on top of low-level technologies, user can avoid dealing with the *transport layer*.
- BSPlib already improves upon MPI in this regard.

Goals of Bulk

- Unified and *modern* interface for distributed and parallel computing.
- Works accross a wide variety of platforms, flexible *backends*.
- Shorter, safer, makes it easier to write (correct) programs.

BSPlib vs Bulk: Hello world

```
#include <bsp.h>

int main() {
    bsp_begin(bsp_nprocs());
    int s = bsp_pid();
    int p = bsp_nprocs();
    printf("Hello World from processor %d / %d", s, p);
    bsp_end();

    return 0;
}
```

BSPlib vs Bulk: Hello world

```
#include <bulk/bulk.hpp>
#include <bulk/backends/mpi/mpi.hpp>

int main() {
    bulk::mpi::environment env;
    env.spawn(env.available_processors(), [](auto& world) {
    auto s = world.rank();
    auto p = world.active_processors();

    world.log("Hello world from processor %d / %d!", s, p);
    });
}
```

BSPlib vs Bulk: Registering variables

```
// BSPlib
int x = 0;
bsp_push_reg(&x, sizeof(int));
bsp_sync();
...
bsp_pop_reg(&x);

// Bulk
auto x = bulk::var<int>(world);
```

BSPlib vs Bulk: Simple distributed variables

```
// BSPlib
int b = 3;
bsp_put(t, &b, &x, 0, sizeof(int));

int c = 0;
bsp_get(t, &x, 0, &c, sizeof(int));

bsp_sync();

// Bulk
x(t) = 3;
auto c = x(t).get();

world.sync();
```

BSPlib vs Bulk: Distributed arrays

```
// BSPlib
int* xs = malloc(10 * sizeof(int));
bsp_push_reg(xs, 10 * sizeof(int));
bsp_sync();

int ys[3] = {2, 3, 4};
bsp_put(t, ys, xs, 2, 3 * sizeof(int));
int z = 5;
bsp_put(t, &z, xs, 0, sizeof(int));

bsp_sync();

...

bsp_pop_reg(xs);
free(xs);
```

BSPlib vs Bulk: Distributed arrays

```
// Bulk
auto xs = bulk::coarray<int>(world, 10);
xs(t)[{2, 5}] = {2, 3, 4};
xs(t)[0] = 5;

world.sync();
```

BSPlib vs Bulk: Message passing

```
// BSPlib
int s = bsp_pid();
int p = bsp_nprocs();

int tagsize = sizeof(int);
bsp_set_tagsize(&tagsize);
bsp_sync();

int tag = 1;
int payload = 42 + s;
bsp_send((s + 1) % p, &tag, &payload, sizeof(int));
bsp_sync();

int packets = 0;
int accum_bytes = 0;
bsp_qsize(&packets, &accum_bytes);

int payload_in = 0;
int payload_size = 0;
int tag_in = 0;
for (int i = 0; i < packets; ++i) {
    bsp_get_tag(&payload_size, &tag_in);
    bsp_move(&payload_in, sizeof(int));
    printf("payload: %i, tag: %i", payload_in, tag_in);
}
```

BSPlib vs Bulk: Message passing

```
// Bulk
auto s = world.rank();
auto p = world.active_processors();

auto q = bulk::queue<int, int>(world);
q(world.next_rank()).send(1, 42 + s);
world.sync();

for (auto [tag, content] : queue) {
    world.log("payload: %i, tag: %i", content, tag);
}
```

Bulk: Addtional features

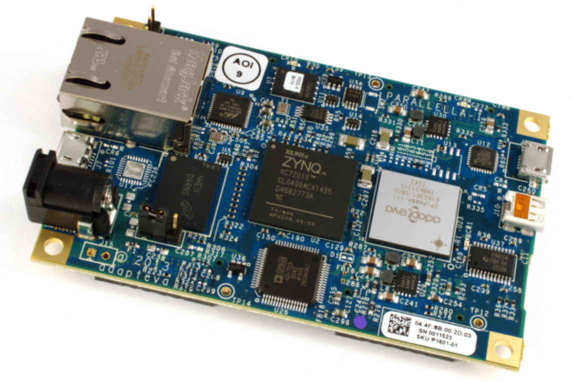
```
// Generic queues
auto q = bulk::queue<int, int, int, float[]>(world);
q(t).send(1, 2, 3, {4.0f, 5.0f, 6.0f});
world.sync();

for (auto [i, j, k, values] : queue) {
    // ...
}

// Standard containers
std::sort(q.begin(), q.end());

auto maxs = bulk::gather_all(world, max);
max = *std::max_element(maxs.begin(), maxs.end());

// Skeletons
// result_1 + result_2 + ...  + result_p
auto alpha = bulk::foldl(result, std::plus<int>());
```

Summary of Bulk

- Modern interface for writing parallel programs, safer and clearer code
- Works together with other libraries because of generic containers and higher-level functions.
- Works across more (mixed!) platforms than competing libraries (because of the backend mechanism).
- Open-source, MIT licensed. Documentation at `jwbuurlage.github.io/Bulk`. Joint work with Tom Bannink (CWI).

BSP on Exotic Systems

Parallella



- ‘*A supercomputer for everyone*, with the lofty goal of “democratizing access to parallel computing’
- Crowd-funded development board, raised almost $1M in 2012.

Epiphany co-processor

- $N \times N$ grid of RISC processors, clocked by default at 600 MHz (current generations have 16 or 64 cores).
- Efficient communication network with '*zero-cost start up*' communication. Asynchronous connection to *external memory pool* using DMA engines (used for software caching).
- Energy efficient @ 50 $\mathrm{GFLOPs/W}$ (single precision), in 2011, top GPUs about $5\times$ less efficient.

Epiphany memory

- Each Epiphany core has 32 kB of **local memory**, on 16-core model 512 kB available in total.
- On each core, the kernel binary and stack already take up a large section of this memory. Duplication.
- On the Parallella, there is 32 MB of **external RAM** shared between the cores, and 1 GB of additional RAM accessible from the ARM host processor.

Many-core co-processors

- Applications: Mobile, Education, possibly even HPC.
- Specialized (co)processors for AI, Computer Vision gaining popularity.
- *KiloCore* (UC Davis, 2016). **1000 processors** on a single chip.
- Bulk provides the same interface for programming the Epiphany co-processor as for programming distributed computer clusters! BSP algorithms can be used for this platform when modified slightly for streamed data[5].

[5] JB, Tom Bannink, Abe Wits. *Bulk-synchronous pseudo-streaming algorithms for many-core accelerators*. arXiv:1608.07200 [cs.DC], 2016

Epiphany BSP

- Parallella: powerful platform, especially for students and hobbyists. Suffers from poor tooling.
- Epiphany BSP, implementation of the BSPlib standard for the Parallella.
- Custom implementations for many rudimentary operations: memory management, printing, barriers.

Hello World: ESDK (124 LOC)

```c
// host

const unsigned ShmSize = 128;
const char ShmName[] = "hello_shm";
const unsigned SeqLen = 20;

int main(int argc, char *argv[])
{
    unsigned row, col, coreid, i;
    e_platform_t platform;
    e_epiphany_t dev;
    e_mem_t    mbuf;
    int rc;

    srand(1);

    e_set_loader_verbosity(H_D0);
    e_set_host_verbosity(H_D0);

    e_init(NULL);
    e_reset_system();
    e_get_platform_info(&platform);

    rc = e_shm_alloc(&mbuf, ShmName,
         ShmSize);
    if (rc != E_OK)
        rc = e_shm_attach(&mbuf, ShmName
             );
    // ...
```

```c
// kernel

int main(void) {
    const char          ShmName[] = "
         hello_shm";
    const char          Msg[] = "Hello 
         World from core 0x%03x!";
    char                buf[256] = { 0 };
    e_coreid_t          coreid;
    e_memseg_t          emem;
    unsigned            my_row;
    unsigned            my_col;


    // Who am I? Query the CoreID from
         hardware.
    coreid = e_get_coreid();
    e_coords_from_coreid(coreid, &my_row
         , &my_col);

    if ( E_OK != e_shm_attach(&emem,
         ShmName) ) {
        return EXIT_FAILURE;
    }

    snprintf(buf, sizeof(buf), Msg,
         coreid);
    // ...
```

Hello World: Epiphany BSP (18 LOC)

```c
// host

#include <host_bsp.h>
#include <stdio.h>

int main(int argc, char** argv) {
    bsp_init("e_hello.elf", argc, argv);

    bsp_begin(bsp_nprocs());

    ebsp_spmd();

    bsp_end();

    return 0;
}
```

```c
// kernel

#include <e_bsp.h>

int main() {
    bsp_begin();

    int n = bsp_nprocs();
    int p = bsp_pid();

    ebsp_printf("Hello world from core %
        d/%d", p, n);

    bsp_end();

    return 0;
}
```

BSP on low-memory

- Limited local memory, *classic* BSP programs can not run.
- Primary goal should be to minimize communication with external memory.
- Many known performance models can be applied to this system (EM-BSP, MBSP, Multi-BSP), **no portable way to write/develop algorithms**.

BSP accelerator

- We view the Epiphany processor as a BSP computer with **limited local memory** of capacity L.
- We have a **shared external memory** unit of capacity E, from which we can read data asynchronously with **inverse bandwidth** e.
- Parameter pack: (p, r, g, l, e, L, E).

Parallella as a BSP accelerator

- $p = 16$, $p = 64$
- $r = (600 \times 10^6)/5 = 120 \times 10^6 \text{ FLOPs}^{(*)}$
- $l = 1.00 \text{ FLOP}$
- $g = 5.59 \text{ FLOP/word}$
- $e = 43.4 \text{ FLOP/word}$
- $L = 32 \text{ kB}$
- $E = 32 \text{ MB}$

(*): In practice one FLOP every 5 clockcycles, in theory up to 2 FLOPs per clockcycle.

External data access: streams

- *Idea:* present the input of the algorithm as **streams** for each core. Each stream consists of a number of **tokens**.
- The ith stream for the sth processor:

$$\Sigma_i^s = (\sigma_1, \sigma_2, \ldots, \sigma_n)$$

- Tokens fit in local memory: $|\sigma_i| < L$.
- We call the BSP programs that run on the tokens loaded on the cores hypersteps.

Structure of a program

- In a hyperstep, while the computation is underway, the next tokens are loaded in (asynchronously).
- The time a hyperstep takes is either **bound by bandwidth or computation**.
- Our cost function:

$$\tilde{T} = \sum_{h=0}^{H-1} \max\left(T_h, e \sum_i C_i\right).$$

Here, C_i is the token size of the ith stream, and T_h is the (BSP) cost of the hth hyperstep.

Pseudo-streaming

- In video-streaming by default the video just ‘runs’. But viewer can skip ahead, rewatch portions. In this context referred to as pseudo-streaming.
- Here, by default the next logical token is loaded in. But programmer can *seek* within the stream.
- This minimizes the amount of code necessary for communication with external memory.
- We call the resulting programs **bulk-synchronous pseudo-streaming** algorithms.

BSPlib extension for streaming

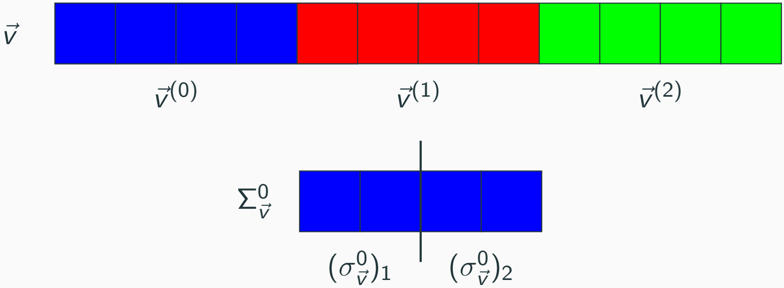
```c
// host
void* bsp_stream_create(
        int processor_id,
        int stream_size,
        int token_size,
        const void* initial_data);

// kernel
int bsp_stream_open(int stream_id);
int bsp_stream_close(int stream_id);
```

BSPlib extension for streaming (2)

```
int bsp_stream_move_down(
        int stream_id,
        void** buffer,
        int preload);

int bsp_stream_move_up(
        int stream_id,
        const void* data,
        int data_size,
        int wait_for_completion);

void bsp_stream_seek(
        int stream_id,
        int delta_tokens);
```

Example 1: Inner product

- *Input*: vectors $\vec{v}, \vec{u}$ of size n
- *Output*: $\vec{v} \cdot \vec{u} = \sum_i v_i u_i$.



Example 1: Inner product (cont.)

- *Input*: vectors $\vec{v}, \vec{u}$ of size n
- *Output*: $\vec{v} \cdot \vec{u} = \sum_i v_i u_i$.

1. Make a p-way distribution of $\vec{v}, \vec{w}$ (e.g. in blocks), resulting in subvectors $\vec{v}^{(s)}$ and $\vec{u}^{(s)}$.
2. These subvectors are then split into tokens that each fit in L. We have two streams for each core s:

$$\Sigma_{\vec{v}}^{s} = ((\sigma_{\vec{v}}^{s})_1, (\sigma_{\vec{v}}^{s})_2, \ldots, (\sigma_{\vec{v}}^{s})_H),$$

$$\Sigma_{\vec{u}}^{s} = ((\sigma_{\vec{u}}^{s})_1, (\sigma_{\vec{u}}^{s})_2, \ldots, (\sigma_{\vec{u}}^{s})_H).$$

3. Maintain a partial answer α_s throughout the algorithm, add $(\sigma_{\vec{v}}^{s})_h \cdot (\sigma_{\vec{u}}^{s})_h$ in the hth hyperstep. After the final tokens, sum over all α_s.

Example 2: Matrix multiplication

- *Input*: Matrices A, B of size $n \times n$
- *Output*: $C = AB$

We decompose the (large) matrix multiplication into smaller problems that can be performed on the accelerator (with $N \times N$ cores). This is done by decomposing the input matrices into $M \times M$ **outer blocks**, where M is chosen suitably large.

$$AB = \left(\begin{array}{c|c|c|c} A_{11} & A_{12} & \dots & A_{1M} \\ \hline A_{21} & A_{22} & \dots & A_{2M} \\ \hline \vdots & \vdots & \ddots & \vdots \\ \hline A_{M1} & A_{M2} & \dots & A_{MM} \end{array}\right) \left(\begin{array}{c|c|c|c} B_{11} & B_{12} & \dots & B_{1M} \\ \hline B_{21} & B_{22} & \dots & B_{2M} \\ \hline \vdots & \vdots & \ddots & \vdots \\ \hline B_{M1} & B_{M2} & \dots & B_{MM} \end{array}\right)$$

Example 2: Matrix multiplication (cont.)

We compute the **outer blocks** of C in row-major order. Since:

$$C_{ij} = \sum_{k=1}^{M} A_{ik} B_{kj},$$

a complete outer block is computed every M hypersteps, where in a hyperstep we perform the multiplication of two outer blocks of A and B.

Each block is again decomposed into **inner blocks** that fit into a core:

$$A_{ij} = \left(\begin{array}{c|c|c|c} (A_{ij})_{11} & (A_{ij})_{12} & \dots & (A_{ij})_{1N} \\ \hline (A_{ij})_{21} & (A_{ij})_{22} & \dots & (A_{ij})_{2N} \\ \hline \vdots & \vdots & \ddots & \vdots \\ \hline (A_{ij})_{N1} & (A_{ij})_{N2} & \dots & (A_{ij})_{NN} \end{array}\right).$$

Example 2: Matrix multiplication (cont.)

The streams for core (s, t) are the inner blocks of A that belong to the core, laid out in row-major order, and the inner blocks of B in column-major order.

$$\Sigma_{st}^{A} = \underbrace{(A_{11})_{st}(A_{12})_{st}\dots(A_{1M})_{st}}_{\circlearrowright\ M\ \text{times}}\ \underbrace{(A_{21})_{st}(A_{22})_{st}\dots(A_{2M})_{st}}_{\circlearrowright\ M\ \text{times}}$$
$$\dots\underbrace{(A_{M1})_{st}(A_{M2})_{st}\dots(A_{MM})_{st}}_{\circlearrowright\ M\ \text{times}},$$

$$\Sigma_{st}^{B} = (B_{11})_{st}(B_{21})_{st}\dots(B_{M1})_{st}(B_{12})_{st}(B_{22})_{st}$$
$$\underbrace{\dots(B_{M2})_{st}(B_{13})_{st}\dots(B_{1M})_{st}(B_{2M})_{st}\dots(B_{MM})_{st}}_{\circlearrowright\ M\ \text{times}}.$$

Example 2: Matrix multiplication (cont.)

In a hyperstep a suitable BSP algorithm (e.g. Cannon's algorithm) is used for the matrix multiplication on the accelerator.

We show that the cost function can be written as:

$$\tilde{T}_{\text{cannon}} = \max\left(2\frac{n^3}{N^2} + \frac{2Mn^2}{N}g + NM^3 l,\ 2\frac{Mn^2}{N^2}e\right).$$

Thanks

If you want to do your final project on something related to Epiphany BSP and/or Bulk, let me know!