Cell Based Servers for Next-Gen Games

Cell BE Online Game Prototype

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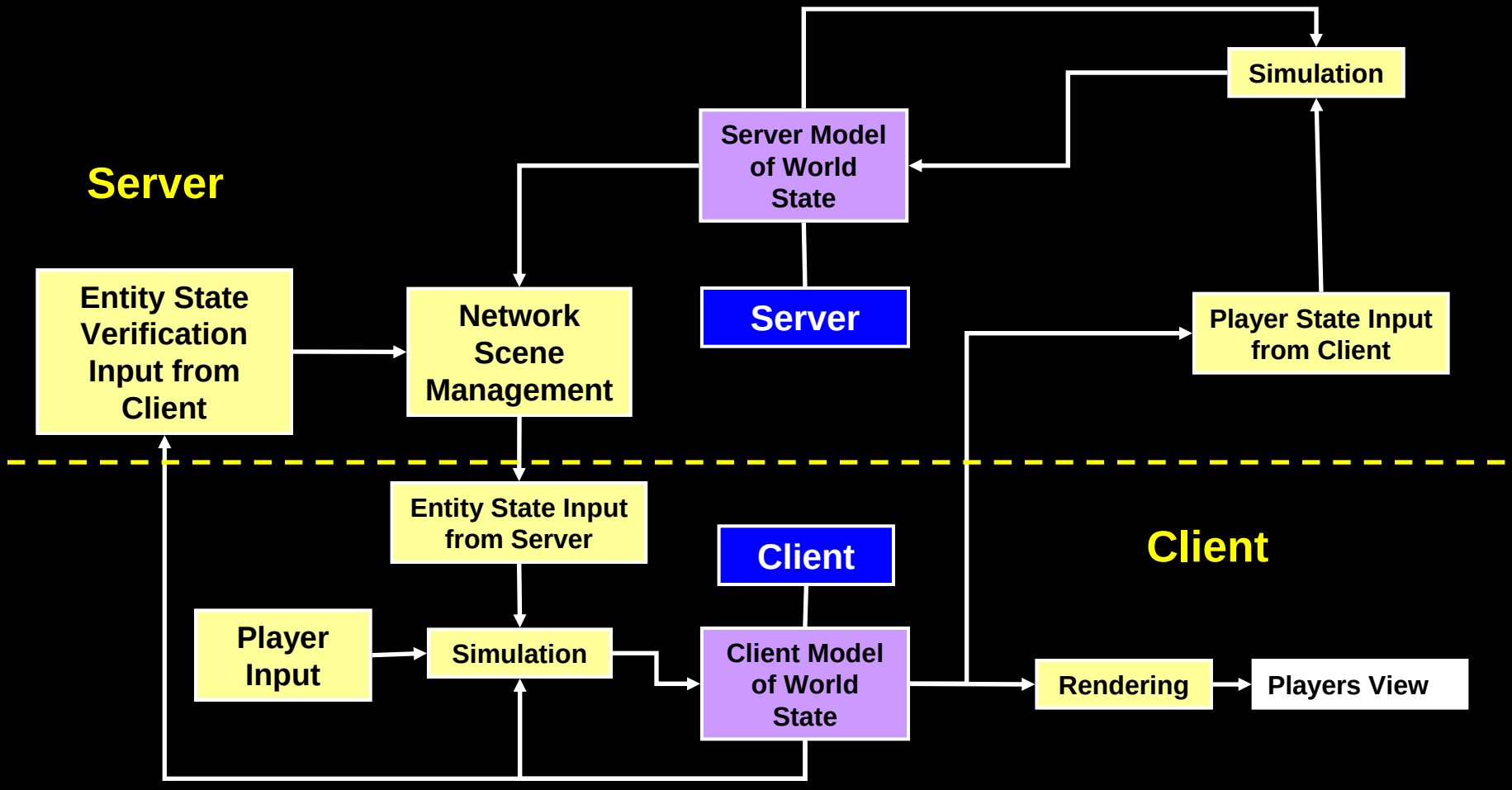
Agenda

- Motivation for Research
- Flow & Execution of Prototypical Online Game
- Operation of Physics Engine
- Bandwidth Management
- Performance
- Future Work

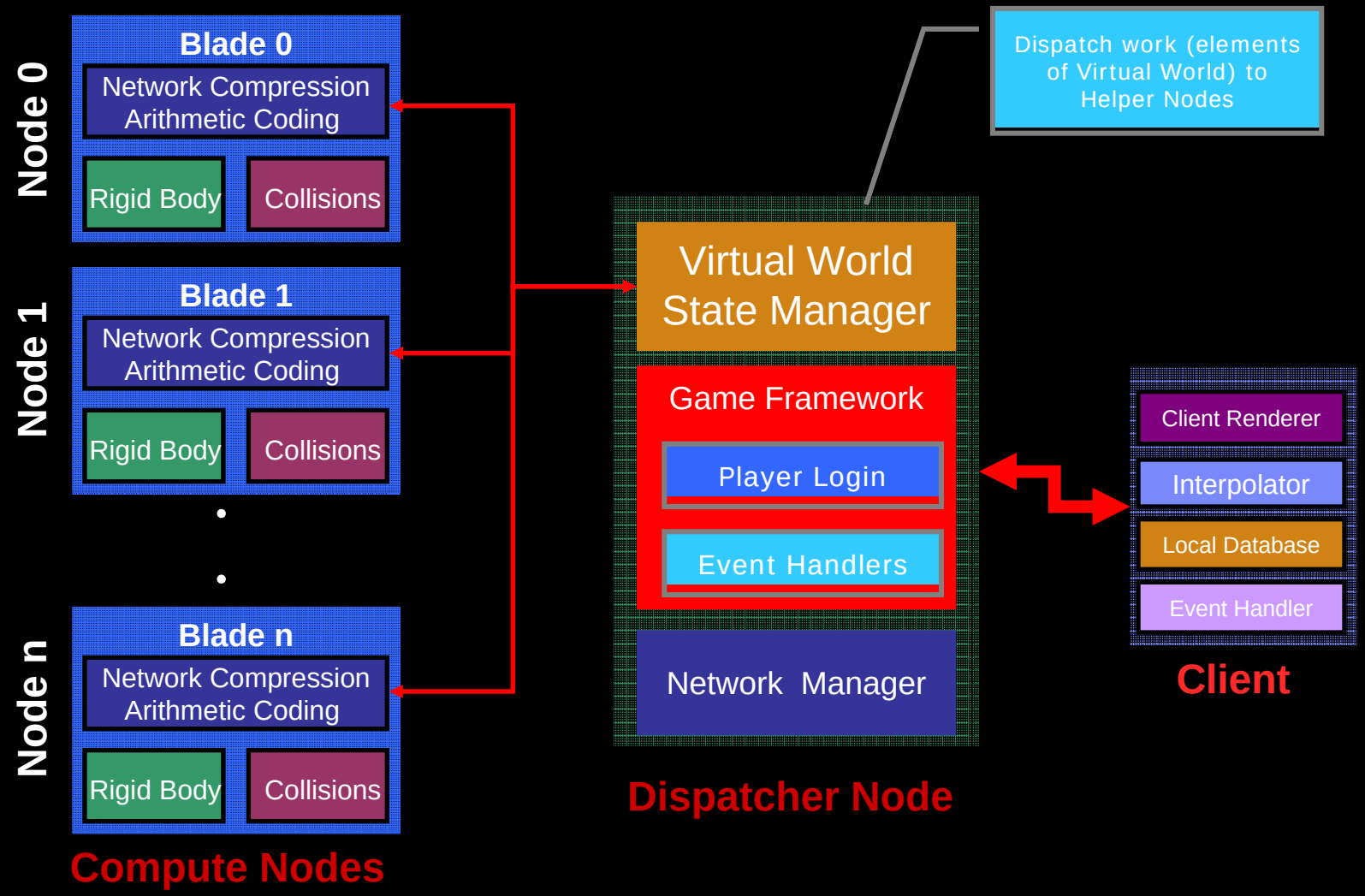
Motivation: Server-side Physically Based Modeling

- Enable the next generation MMOGs & virtual environments
  - Current online video games perform limited amount of physical simulation
    - Not enough client CPU resources
    - Bandwidth & Latency between processing nodes prohibitive to achieving real time performance
- Enable complex visual F/X movies on large servers

Game Execution Flow



Server-side state: Stateless model



Bandwidth Requirements

Uncompressed data transmitted to compute notes:

Dispatcher-to-Compute node Communications	
Field Name	**Size (in 32-bit floats)**
Position	3
Orientation	4
Linear Velocity	3
Angular Velocity	3
Mass	1
Inertia Tensor	6
Coefficient of Friction	1
Collision Flags	1
Collision Body	(unbounded)

Only variable data transmitted back to dispatcher:

Compute node-to-Dispatcher communications	
Field Name	**Size (in 32-bit floats)**
Position	3
Orientation	4
Linear Velocity	3
Angular Velocity	3

Dispatcher-to-Compute node Communications (added entries for compressed body shape)	
Field Name	**Size (in 32-bit floats)**
Body Flags	1
Body Scale	1
Body Shape Index	1

Reduce the bandwidth requirements by using a dictionary index and some scaling and options information for each body.

Collision Detection

- Broad-phase collision detection
  - simple bounding box culling
- Mid-phase collision detection consists of a 1D sort and sweep of the axis-aligned bounding boxes
- Narrow-phase collision detection uses a proprietary algorithm to compute a set of contacts between a pair of convex hulls

➢ All collision detection being moved to SPEs

Server Side Physics Loop

Runtime steps:

1. **Collision detection** (broad-, mid-, and narrow-phase)
2. **Revise lists** of active vs. sleeping bodies
3. **Partition active bodies** into non-interacting groups
4. **Decouple** to break up groups which are too large to fit in SPE local store
5. **Integrate** to obtain positions of bodies for next step
6. **Adjust step size** if integration step fails

Rigid Body Dynamics

- Objects in the game world are represented by one or more rigid bodies;
  - a sparsely populated world will have about 1000 rigid bodies
    - 6 degrees of freedom per rigid body
  - Represented by 3-tuples, but stored as padded vector floats:
    - Linear position of the body's center of mass
    - Linear velocity of body
    - Angular velocity of body
  - Orientation representation is a unit quaternion or matrix33
- Forces and constraints define interactions between rigid bodies
  - allow joints, hinges, etc. to be implemented
- Physics provides real-time simulation of the interaction between rigid bodies

Sparse Matrix Data Structures on Cell

- Matrix is block-sparse with 6x6 blocks
  - diagonal blocks represent bodies and
  - off-diagonal blocks represent forces between bodies
- Typical 65-body group has ~200 nonzero blocks in a 65x65-block matrix
- Diagonal elements are assumed nonzero and are stored as a “block” vector for fast access
- Off-diagonal elements are stored in linked lists (one per block row) of block data and associated block column position
- 6x6 float block data is currently stored in column-major form in a padded 8x6 block for ease of access
- Vectors used in sparse matrix multiplication are similarly stored as vector floats on SPE with one unused float per three elements

Numerical Integration

- Game world is partitioned into non-interacting groups of 1 or more rigid bodies which can be simulated on a single SPU
  - maximum of about 120 bodies per group
- SPU performs semi-implicit integration step for a second-order rigid body dynamics system
  - uses conjugate gradient squared algorithm
  - basic operation is multiplication of a 6x6-block-sparse matrix by vector
- Output of the integration step
  - change in linear velocity and angular velocity for each rigid body over one time step

SPU Implementation: Rigid Body Structures

Input structure

```
struct Rigid_Body {
        //state
        Vec3 position;
        Matrix33 orientation;
        Vec3 velocity;
        Vec3 angular_velocity
        //mass params
        float inverse_mass;
        Matrix33 inverse_inertia;
        //other params:
        float coeffecient_friction;
        float coeffecient_damping;
        ...
} bodies[num_bodies];
```

Output structure

```
struct Rigid_Body_Step {
        Vec3 delta_velocity;
        Vec3 delta_angular_velocity;
} delta_v[num_bodies];
```

Forces can be global, unary, or binary

- Examples of binary forces:

```
struct Point_To_Point_Constraint_Force
{
        int index_body_a;
        int index_body_b;
        Vec3 point_body_space_a;
        Vec3 point_body_space_b;
};
struct Contact_Force {
        int index_body_a;
        int index_body_b;
        Vec3 point_world_space;
        Vec3 normal_world_space;
        float penetration;
};
```

Intermediate data structures

Vec4 v0[2*num_bodies];
Vec4 f0[2*num_bodies];

- Six component vectors are padded out to 8 components, with one float of padding on each of the linear and angular components
- The most complicated data structure is the block sparse matrix:

```
struct Block_Sparse_Matrix {
        struct Block {
                Matrix86 m;
                int column_index;
                Element* pointer_next;
        };
        Block* rows[NUM_BODIES];
};
```

- The logically 6x6 blocks are padded to 8x6. The matrix is stored in a column major fashion, with padding on the 4th and 8th element to match padding in v0 and f0

Numerical Integration Steps

Steps 1-4 are performed on the SPE.

1. Calculate the components of **A** and **b**. **v0** and **W** are trivial to extract. **f0** must be calculated. **df_dx** and **df_dv** both require considerable computational effort to calculate.
2. Form **A** and **b**
3. solve **A*delta_v = b** by a conjugate gradient method.
4. step the system from **Y0** to **Y1** by **delta_v**

Conjugate Gradient Squared

Why was conjugate gradient squared chosen?

- The preferred choice is bi-conjugate gradient, but this requires multiplies by ***A*** transpose
- The sparse matrix transpose times vector can be written in a row-oriented fashion, but having the inner 6x6 logical block efficiently support both multiplication with a logical 6-vector and multiplication of its transpose with a logical 6-vector may be more expensive than the alternative – conjugate gradient squared.
  - Caching the transpose of the blocks would likely take too much memory

SPU Conjugate Gradient Squared

```
int SPU_conjugate_gradient_squared (
      int* Pdest_num_iters,
      vf3 x[],
     const SPU_Sparse_Matrix_Element* const
    A[],
     const vf3 pb[],
     int num_bodies)
{
        nv = 2*num_bodies;

        float rho_1=0.0f, rho_2=0.0f, alpha=0.0f,
    beta=0.0f;

        int iter = 0;
        float resid = 0.0f;

      vf3* b = (vf3*)pb;

        const int max_iters = 2*6*num_bodies;
//
        float bb = vec_dot(b,b);
        vector float bbb = spu_splats(bb);
        bbb = _sqrtf4(bbb);
        const float norm_b = spu_extract(bbb, 0);
```

```
if (norm_b < .0001f)
        return 0;

  const float rel_tol = 0.001f;
  const float abs_tol = 0.001f;

  neg_mul_add(r, A, x, b);
  vec_assign(r_tilde, r);

  while (1) {
        float rr = vec_dot(r, r);
        vector float rrr =
        spu_splats(rr);
        rrr = _sqrtf4(rrr);
        rr = spu_extract(rrr, 0);
        resid = rr/norm_b;
```

SPU Conjugate Gradient Squared *(continued)*

```
if ((resid < rel_tol) || (rr < abs_tol)) {
    return 0;
 }
else if (iter >= max_iters) {
     return 1;
  }
 ++*Pdest_num_iters;

 rho_1 = vec_dot(r_tilde, r);

 if (rho_1 == 0.0f) {
     return 2;
  }

  if (iter == 0) {
     vec_assign(u, r);
     vec_assign(p, u);
   }
   else {
      beta = rho_1/rho_2;
      vec_add_scaled(u, r, beta, q);
      vec_add_scaled(p, q, beta, p);
      vec_add_scaled(p, u, beta, p);
    }
```

```
     vec_assign(p_hat, p);   //p_hat =
precond.solve(p);
      mul(v_hat, A, p_hat);
       float den = vec_dot(r_tilde, v_hat);
       if (den == 0.0f) {
           return 3;
        }
        alpha = rho_1/den;

        vec_add_scaled(q, u, -alpha, v_hat);
        vec_add(u, u, q);
        vec_assign(u_hat, u);   //u_hat =
precond.solve(u);
        vec_add_scaled(x, x, alpha, u_hat);
         mul(q_hat, A, u_hat);
         vec_add_scaled(r, r, -alpha, q_hat);

         rho_2 = rho_1;
         ++iter;
       } // end while
       return 0;
} // end of spu_conjugate_gradient_squared
```

SPU Conjugate Gradient Squared Method

- The conjugate gradient squared method only requires A times a vector – however, it has been found in practice to converge more slowly.
- Each iteration of the conjugate gradient performs two matrix vector products along with a handful of vector scales, adds, and inner products. The matrix product is the only non-trivial operation. It looks like this:

```
void mul(Vec8* res, const Block_Sparse_Matrix2& A, const Vec8* x)
{
        for (int i = 0; i < num_bodies; ++i) {
                Vec8 sum = 0;
                for (Block* b=A.rows[i]; b; b = b->pointer_next)
                        sum += b->m * x[b->column_index];
                res[i] = sum;
        }
}
```

Where , b->m * x[b->column_index] is pseudo code for Column_Major_Matrix86 times Vec8 which is basically trivial SPE code.

SPU Sparse Matrix Multiply Code

```
void mul(vf4 d[], const SPU_Sparse_Matrix_Element* const A[], const vf4 x[])
{
	PROFILER(mul);
	int i;
	for (i=0; i < nv/2; ++i) {
		const SPU_Sparse_Matrix_Element* p = A[i];

		vf3 s0 = vf3_zero;
		vf3 s1 = vf3_zero;

		while (p) {
			int j = p->j;
			s0 = spu_add(s0, xform_vf3(&p->a.a[0][0], x[2*j+0]));
			s0 = spu_add(s0, xform_vf3(&p->a.a[0][1], x[2*j+1]));
			s1 = spu_add(s1, xform_vf3(&p->a.a[1][0], x[2*j+0]));
			s1 = spu_add(s1, xform_vf3(&p->a.a[1][1], x[2*j+1]));

			p = p->Pnext;
		}
		d[2*i+0] = s0;
		d[2*i+1] = s1;
	}
}
```

Memory constraints and workload size

- The number of matrix blocks required is less than num_bodies + 2*num_binary_forces
- A typical 65 rigid body scene had approximately 400 contacts
- SPU memory usage for integrating this example scene follows:

Input:

num_bodies*sizeof(Padded(Rigid_Body)) = 65*160B = 10400B
num_contacts*sizeof(Padded(Contact_Force)) = 400*48B = 19200B
TOTAL= 29600B

Output:

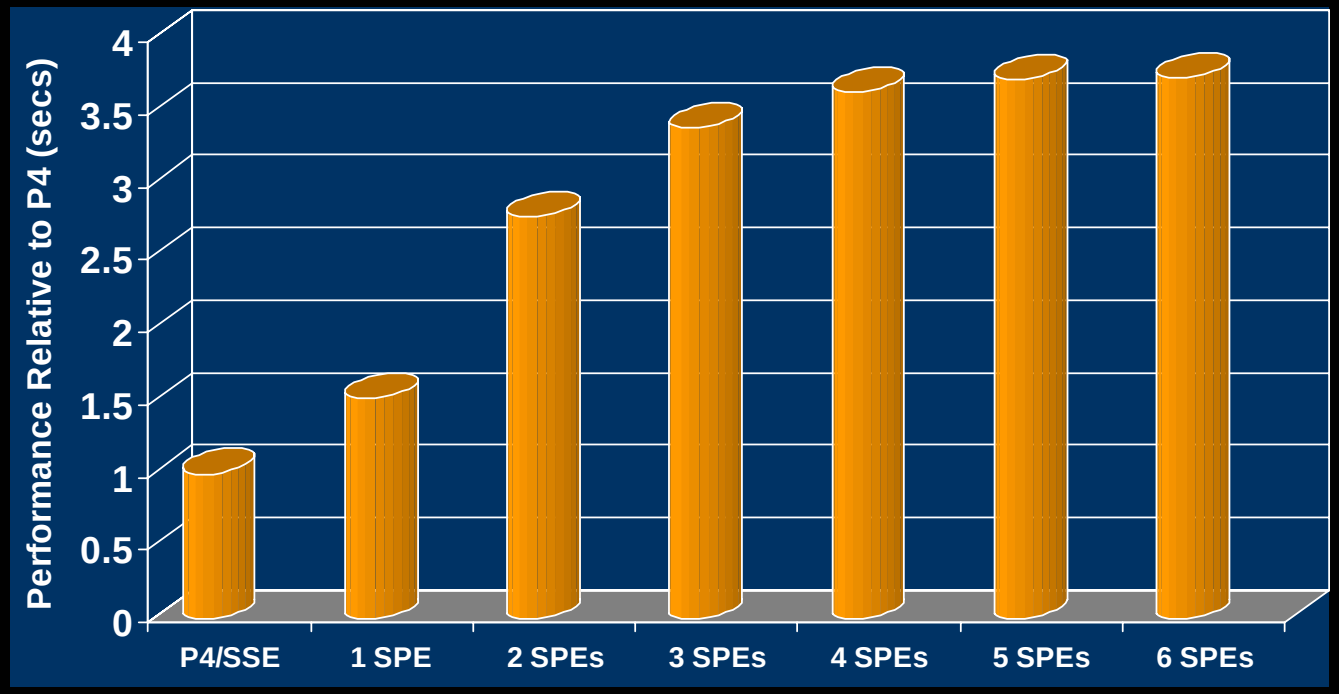
num_bodies*sizeof(Padded(Rigid_Body_Step)) = 65*32B = **2080B**

Intermediate:

num_bodies*sizeof(Padded(W_Element)) = 65*64B = 4160B
num_vectors*num_bodies*sizeof(Padded(Vec6)) = 8*65*32B = 16640B
num_bodies*sizeof(Block*) = 65*4B = 260B
num_blocks*sizeof(Padded(Block)) = 200*208B = 41600B
TOTAL = 62660B

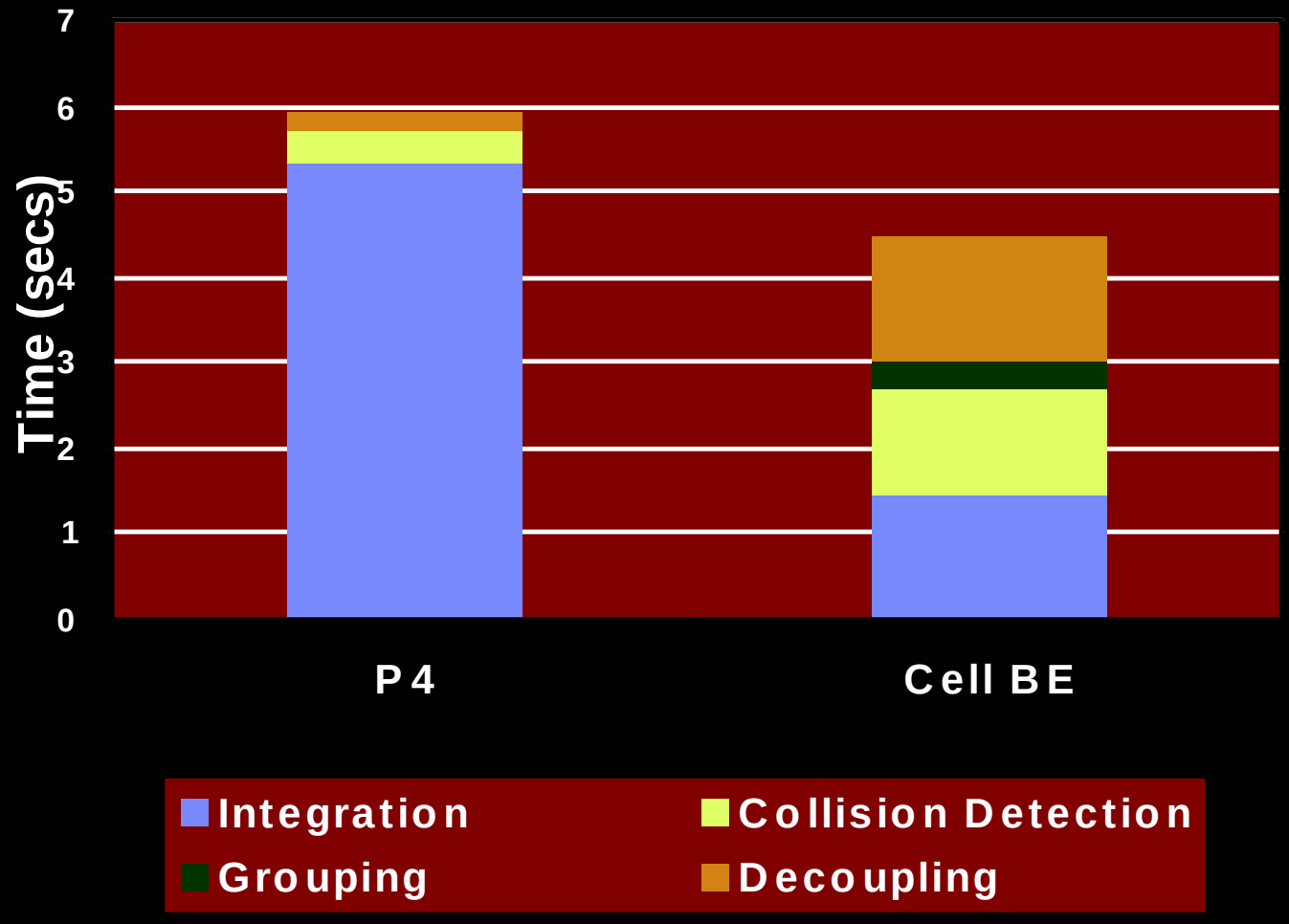
- Including double buffering the input and output areas, we use a **total of 126,020B**
- Maximum workload is probably less than 120 bodies

Integration Core Performance



3.2 Ghz P4/SSE versus 2.4 Ghz Cell BE
1 SPE about 1.5x P4/SSE

Relative Code Segment Performance



Cell BE Code Sizes for Numerical Integration

- Currently 7,104 lines of SPE code
  - 2,741 lines of human written code
  - 4,363 lines of generated code
- 4,536 lines of PPE support code
  - Decouple
  - Pack
  - Unpack
  - Schedule
- 828 lines of PPE library code
  - DMA commands wrapper/emulation
  - Scalar/SSE/VMX emulation of SPE ops

Conclusions & Next Steps

- **SPEs are very fast and can provide significant speedup**
- **DMA engine provides low-latency, high bandwidth data movement**
- **PPE should be used as a control processor**

  Maximum PPE performance achieved by using 2 PPE threads
- **Move as much of code to SPEs – even scalar code**
  - Collision detection being moved to SPEs
  - Ultimately grouping, de-coupling and network scene management should be moved to SPEs.
- **Data structures should be optimized for transfer to SPE LS**
  - Lot of PPE cycles wasted in packing and unpacking data
- **Add more destructible-body and soft-body dynamics**

Cell Broadband Engine: Online Game Prototype

Thank You!

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