Efficient Distributed Stochastic Dual Coordinate Ascent

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Problem Overview - The Primal Problem

Many machine learning problems can be formulated as the Regularized Finite Sum Minimization (RFSM) problem.

$$\min_{w \in \mathbb{R}^d} P(w) \tag{1}$$

where

$$P(w) = \frac{1}{n} \sum_{i=1}^{n} \phi(w^\top x_i, y_i) + \lambda g(w)$$

$$w, x_i \in \mathbb{R}^d, \text{ for } i = 1, \ldots, n$$

$$y_i \in \mathbb{R}, \text{ for } i = 1, \ldots, n$$

$$\phi(z, y) \text{ is convex in } z$$

$$g(w) \text{ is convex in } w$$

Problem Overview - The Dual Problem

We consider the case when $g(w) = \frac{1}{2}\|w\|_2^2$, then the dual problem is given by

$$\max_{\alpha \in \mathbb{R}^n} D(\alpha) \tag{2}$$

where

$$D(\alpha) = \frac{1}{n}\sum_{i=1}^{n} -\phi_i^*(-\alpha_i) - \frac{\lambda}{2}\left|\left|\frac{1}{\lambda n}\sum_{i=1}^{n}\alpha_i x_i\right|\right|^2$$

$$x_i \in \mathbb{R}^d, \text{ for } i = 1, \ldots, n$$

$$\alpha \in \mathbb{R}^n$$

$$\phi_i^*(u) = \max_z (zu - \phi_i(z))$$

Related Work

The two key papers influencing our work are:

- Stochastic Dual Coordinate Ascent (SDCA) [Shalev-Shwartz and Zhang, 2013]
- Distributed SDCA [Yang, 2013, Yang et al., 2013]

What is SDCA?

- **SDCA** - randomly pick a coordinate axis of $\alpha \in \mathbb{R}^n$, find update that best improves the objective

- **Distributed SDCA** - randomly pick k coordinate axes of $\alpha \in \mathbb{R}^n$, simultaneously find updates that best improve the objective (independently)

SDCA Algorithm

SDCA procedure:

- Let $w^{(0)} = w(\alpha^{(0)})$
- **Iterate**: for $t = 1, 2, \ldots, T$
  - Randomly pick i
  - Find $\triangle\alpha_i$ to maximize
    $-\phi_i^*(-(\alpha^{(t-1)} + \triangle\alpha_i)) - \frac{\lambda n}{2}\|w^{(t-1)} + (\lambda n)^{-1}\triangle\alpha_i x_i\|^2$
  - $\alpha^{(t)} \leftarrow \alpha^{(t-1)} + \triangle\alpha_i e_i$
  - $w^{(t)} \leftarrow w^{(t-1)} + (\lambda n)^{-1}\triangle\alpha_i x_i$
- Output (Random option):
  Let $\bar{\alpha} = \alpha^{(t)}$ and $\bar{w} = w^{(t)}$ for some random
  $t \in T_0 + 1, \ldots, T$
  Return $\bar{w}$

Remark: The red steps spend the largest proportion of computing resources.

What if we ran SDCA on the GPU?

Parallelizing SDCA

Two approaches:

- Naive approach: simply parallelize all tensor operations (e.g., dot product, matrix-vector multiplication, etc.)

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- Naive approach: simply parallelize all tensor operations (e.g., dot product, matrix-vector multiplication, etc.)
- Better: mimic the distributed apporach by [Yang, 2013] on a GPU

Implementation

Main Points

The key area of concern:

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- Memory
  - Allocation
  - Communication (via PCIE bus rather than network)
  - How can we cognitive load of writing this code?

Dealing with Memory Allocation

Naive approach:

```
void MemSync::PushToGpu(const vector &x) {
  double *dx;
  int n_bytes = sizeof(double) * x.size();

  // Allocate GPU memory
  cudaMalloc((double**)&dx, n_bytes);

  // Copy data to GPU
  cudaMemcpy(dx, &x[0], n_bytes,
             cudaMemcpyHostToDevice);
}
```

On a small dataset(200 points in $\mathbb{R}^3$) we hit over 200k allocations, which comprised nearly **95%** of the GPU compute time (≈ 13 seconds).

Can we do better?

Can we do better?

Yes!

Dealing with Memory Allocation

Better approach:

```
class MemSync {
  // class code
  static double *dx_;
};
void MemSync::PushToGpu(const vector &x) {
  int n_bytes = sizeof(double) * x.size();

  // Copy data to GPU
  cudaMemcpy(MemSync::dx_, &x[0],
             n_bytes, cudaMemcpyHostToDevice);
}
```

The use of static class pointers reduced the 200k allocations down to only **3 memory allocations**, which comprised only **0.03%** compute time ($\approx 180\mu s$).

What about the cost of communication?

Communication Costs

Copying data to and from the GPU is the next most expensive operation.

- About 50% of the compute time, or 768 ms (using the same toy dataset, after we have fixed the memory allocation issue)

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- Mostly unnecessary!

Communication Costs

Consider the following algorithm using the GPU:

1: $\Delta\omega_i \leftarrow f(\mathbf{x}, \omega)$

2: $\omega_i \leftarrow \omega_i + \Delta\omega_i$

To handle this efficiently we should:

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To handle this efficiently we should:

- Reuse ω in step 2 since we already moved it to the GPU for step 1
- Perform step 2 on the GPU since the data is already there. No need to pull it off and then move it back to the GPU

Communication Costs

The sad reality is this is quite complicated.

- Lots of book-keeping
- Are there edge cases?
- Need to watch out for memory leaks. Remember, **no** GC!

How can we handle this complexity?

Wrappers

We use wrappers (also known as decorators) to add additional functionality to our code. For example,

```
double VectorDotProduct(const vector &x,
                        const vector &y) {
#ifdef GPU
  return VectorDotProduct_gpu(x, y);
#else
  return VectorDotProduct_cpu(x, y);
#endif
}
```

Wrappers

To handle the flow of data from GPU to CPU, as well as book-keeping, we can use something like this:

```
class Data {
  enum DataLocation { Gpu, Cpu };

  // Pointer to GPU memory
  std::unique_ptr<double> dx_
  // Local reference (RAM)
  Eigen::VectorXd x_;
  // DataLocation::Gpu or DataLocation::Cpu
  DataLocation location_;
};
```

What about results?

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- Loading data
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- Algorithm performance tracking
- Expect distributed SDCA to be the fastest, followed by CUDA accelerated SDCA, followed by SDCA

Shalev-Shwartz, S. and Zhang, T. (2013).
Stochastic dual coordinate ascent methods for regularized loss minimization.
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Analysis of distributed stochastic dual coordinate ascent.
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