

# Domain Wall Fermions with 4-d EO preconditioning

## Version 1.4.1

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November 10, 2003

### Abstract

The only difference between version 1.3 and 1.4 is storing projections into lattice temporaries thus degrading performance unnecessary. Presumably, with better neighbor tables this will make it simple to use QMP communication framework, however, care should be taken in making sure the send buffers are continious in memory.

## 1 DEFINITIONS

Here is the definition of the DWF Dirac operator we are using:

$$\begin{aligned}\chi_{s,x} = D\psi &= M_0\psi_{s,x} + \sum_{\mu} \left( (1 + \gamma_{\mu})U_{x,\mu}\psi_{s,x+\hat{\mu}} + (1 - \gamma_{\mu})U_{x-\hat{\mu},\mu}^{\dagger}\psi_{s,x-\hat{\mu}} \right) \\ &+ (1 + \gamma_5)M_s^{(+)}\psi_{s+1,x} + (1 - \gamma_5)M_s^{(-)}\psi_{s-1,x}\end{aligned}$$

where

$$M_s^{(+)} = \begin{cases} 1, & \text{if } s < N_s - 1 \\ -m_f, & \text{if } s = N_s - 1 \end{cases}$$

and

$$M_s^{(-)} = \begin{cases} 1, & \text{if } s > 0 \\ -m_f, & \text{if } s = 0 \end{cases}$$

We also assume that  $\psi_{N_s,x} = \psi_{0,x}$  and  $\psi_{-1,x} = \psi_{N_s-1,x}$ .

As Kostas has shown, one can do 4-d even/odd preconditioning to DWF in this form. This allows us to concentrate on computing the operator

$$\phi = Q_{ee}^{-1}Q_{eo}\psi$$

Up to a scale factor, one has

$$Q_{ee} = \frac{1 + \gamma_5}{2} \begin{pmatrix} 1 & a & 0 & \cdots & 0 \\ 0 & 1 & a & & 0 \\ \vdots & & & \ddots & \vdots \\ b & 0 & 0 & \cdots & 1 \end{pmatrix} + \frac{1 - \gamma_5}{2} \begin{pmatrix} 1 & 0 & \cdots & 0 & b \\ a & 1 & 0 & & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & \cdots & a & 1 \end{pmatrix}$$

Now,  $a = 2/M_0$ , and  $b = -2m_f/M_0$  are numbers and color structure of  $Q_{ee}$  is trivial.

The trickiest part to do on a vector architecture is computing  $Q_{ee}^{-1}$  with high efficiency. To achieve good performance, we employ a few tricks. First, one  $s$ -slice fits comfortably into L1 cache. This allows us to (a) reuse the  $U$  field, thus reducing memory traffic, and (b) apply  $Q_{ee}^{-1}$  to the result on a  $s$ -slice by slice basis while the result of  $Q_{eo}\psi$  is still in cache.

## 2 $\gamma$ MATRICES

Choice of  $\gamma$ -matrices made in `sse.nw` is still convenient for two reasons:

- $\gamma_5$  is diagonal. It allows one to simplify  $Q_{ee}^{-1}$  computation.
- Signs in  $\gamma_2$  make the final step in  $Q_{eo}$  a tiny bit simpler. It might be not hugely advantageous, but it cuts a bit a number of floating point operations needed, which is good.

The separated projection part reads `psi` sequentially and stores the results into eight buffers `proj[d][xx.Fproj[d]]` rearranging sites to facilitate communication. It is non-obvious, that one loop with one reader and eight writers gives higher performance than eight loops with one reader and eight writers each. A small efficiency study left for the sake of getting something running yesterday.

$$\gamma_1 = 1 \otimes \sigma_2 = \begin{pmatrix} 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{pmatrix}$$

```

⟨Extract 1-d addresses for  $\gamma$ -projections⟩≡
  DiracFermion1d pX(psi[xyzt]);
  HalfFermion1d pxp0(proj[0][xx.Fup[xyzt].d[0]]);

⟨Construct neighbors references⟩≡
  VDiracFermion &pS = pX[s];
  VHalfFermion &pp0 = pxp0[s];

⟨Project  $\gamma_1$  upward link⟩≡
  pp0.v[0][c] = amib(pS.v[0][c], pS.v[1][c]);
  pp0.v[1][c] = amib(pS.v[2][c], pS.v[3][c]);

⟨Unproject and accumulate  $\gamma_1$  upward link⟩≡
  set_ap1b(rs.v[0][c], g[0].v[0][c]);
  set_apib(rs.v[1][c], g[0].v[0][c]);
  set_ap1b(rs.v[2][c], g[0].v[1][c]);
  set_apib(rs.v[3][c], g[0].v[1][c]);

⟨Extract 1-d addresses for  $\gamma$ -projections⟩+≡
  HalfFermion1d pxm0(proj[1][xx.Fdown[xyzt].d[0]]);

⟨Construct neighbors references⟩+≡
  VHalfFermion &pm0 = pxm0[s];

⟨Project  $\gamma_1$  downward link⟩≡
  pm0.v[0][c] = apib(pS.v[0][c], pS.v[1][c]);
  pm0.v[1][c] = apib(pS.v[2][c], pS.v[3][c]);

⟨Unproject and accumulate  $\gamma_1$  downward link⟩≡
  set_ap1b(rs.v[0][c], g[1].v[0][c]);
  set_amib(rs.v[1][c], g[1].v[0][c]);
  set_ap1b(rs.v[2][c], g[1].v[1][c]);
  set_amib(rs.v[3][c], g[1].v[1][c]);

```

$$\gamma_2 = \sigma_1 \otimes \sigma_1 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$\langle \text{Extract 1-d addresses for } \gamma\text{-projections} \rangle + \equiv$   
`HalfFermion1d pxp1(proj[2][xx.Fup[xyzt].d[1]]);`

$\langle \text{Construct neighbors references} \rangle + \equiv$   
`VHalfFermion &pp1 = pxp1[s];`

$\langle \text{Project } \gamma_2 \text{ upward link} \rangle \equiv$   
`pp1.v[0][c] = ap1b(pS.v[0][c], pS.v[2][c]);`  
`pp1.v[1][c] = ap1b(pS.v[1][c], pS.v[3][c]);`

This is a special case. The result of  $Q_{eo}$  is build starting from  $(1 + \gamma_2)$  to save 6 negations.

$\langle \text{Unproject } \gamma_2 \text{ upward link} \rangle \equiv$   
`rs.v[0][c] = g[2].v[0][c];`  
`rs.v[1][c] = g[2].v[1][c];`  
`rs.v[2][c] = g[2].v[0][c];`  
`rs.v[3][c] = g[2].v[1][c];`

$\langle \text{Extract 1-d addresses for } \gamma\text{-projections} \rangle + \equiv$   
`HalfFermion1d pxm1(proj[3][xx.Fdown[xyzt].d[1]]);`

$\langle \text{Construct neighbors references} \rangle + \equiv$   
`VHalfFermion &pm1 = pxm1[s];`

$\langle \text{Project } \gamma_2 \text{ downward link} \rangle \equiv$   
`pm1.v[0][c] = am1b(pS.v[0][c], pS.v[2][c]);`  
`pm1.v[1][c] = am1b(pS.v[1][c], pS.v[3][c]);`

$\langle \text{Unproject and accumulate } \gamma_2 \text{ downward link} \rangle \equiv$   
`set_ap1b(rs.v[0][c], g[3].v[0][c]);`  
`set_ap1b(rs.v[1][c], g[3].v[1][c]);`  
`set_am1b(rs.v[2][c], g[3].v[0][c]);`  
`set_am1b(rs.v[3][c], g[3].v[1][c]);`

$$\gamma_3 = \sigma_2 \otimes \sigma_1 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ i & 0 & 0 & 0 \end{pmatrix}$$

```

⟨Extract 1-d addresses for  $\gamma$ -projections⟩+≡
    HalfFermion1d pxp2(proj[4][xx.Fup[xyzt].d[2]]);

⟨Construct neighbors references⟩+≡
    VHalfFermion &pp2 = pxp2[s];

⟨Project  $\gamma_3$  upward link⟩≡
    pp2.v[0][c] = amib(pS.v[0][c], pS.v[3][c]);
    pp2.v[1][c] = amib(pS.v[1][c], pS.v[2][c]);

⟨Unproject and accumulate  $\gamma_3$  upward link⟩≡
    set_ap1b(rs.v[0][c], g[4].v[0][c]);
    set_ap1b(rs.v[1][c], g[4].v[1][c]);
    set_apib(rs.v[2][c], g[4].v[1][c]);
    set_apib(rs.v[3][c], g[4].v[0][c]);

⟨Extract 1-d addresses for  $\gamma$ -projections⟩+≡
    HalfFermion1d pxm2(proj[5][xx.Fdown[xyzt].d[2]]);

⟨Construct neighbors references⟩+≡
    VHalfFermion &pm2 = pxm2[s];

⟨Project  $\gamma_3$  downward link⟩≡
    pm2.v[0][c] = apib(pS.v[0][c], pS.v[3][c]);
    pm2.v[1][c] = apib(pS.v[1][c], pS.v[2][c]);

⟨Unproject and accumulate  $\gamma_3$  downward link⟩≡
    set_ap1b(rs.v[0][c], g[4].v[0][c]);
    set_ap1b(rs.v[1][c], g[4].v[1][c]);
    set_amib(rs.v[2][c], g[4].v[1][c]);
    set_amib(rs.v[3][c], g[4].v[0][c]);

```

$$\gamma_4 = \sigma_3 \otimes \sigma_1 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

```

⟨Extract 1-d addresses for  $\gamma$ -projections⟩+≡
    HalfFermion1d pxp3(proj[6][xx.Fup[xyzt].d[3]]);

⟨Construct neighbors references⟩+≡
    VHalfFermion &pp3 = pxp3[s];

⟨Project  $\gamma_4$  upward link⟩≡
    pp3.v[0][c] = ap1b(pS.v[0][c], pS.v[1][c]);
    pp3.v[1][c] = am1b(pS.v[2][c], pS.v[3][c]);

⟨Unproject and accumulate  $\gamma_4$  upward link⟩≡
    set_ap1b(rs.v[0][c], g[6].v[0][c]);
    set_ap1b(rs.v[1][c], g[6].v[0][c]);
    set_ap1b(rs.v[2][c], g[6].v[1][c]);
    set_am1b(rs.v[3][c], g[6].v[1][c]);

⟨Extract 1-d addresses for  $\gamma$ -projections⟩+≡
    HalfFermion1d pxm3(proj[7][xx.Fdown[xyzt].d[3]]);

⟨Construct neighbors references⟩+≡
    VHalfFermion &pm3 = pxm3[s];

⟨Project  $\gamma_4$  downward link⟩≡
    pm3.v[0][c] = am1b(pS.v[0][c], pS.v[1][c]);
    pm3.v[1][c] = ap1b(pS.v[2][c], pS.v[3][c]);

⟨Unproject and accumulate  $\gamma_4$  downward link⟩≡
    set_ap1b(rs.v[0][c], g[7].v[0][c]);
    set_am1b(rs.v[1][c], g[7].v[0][c]);
    set_ap1b(rs.v[2][c], g[7].v[1][c]);
    set_ap1b(rs.v[3][c], g[7].v[1][c]);

```

These  $\gamma$ -matrices were chosen to make  $\gamma_5$  diagonal:

$$\gamma_5 = 1 \otimes \sigma_3 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

This, in turn, makes computation of  $Q_{ee}^{-1}\psi$  conceptually easy, because  $(1 \pm \gamma_5)$  acts only on upper/lower Dirac components. Therefore, we need a method to compute inverses of the following two matrices:

$$A = \begin{pmatrix} 1 & a & 0 & \cdots & 0 \\ 0 & 1 & a & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & & \cdots & 1 & a \\ b & 0 & \cdots & 0 & 1 \end{pmatrix} \quad B = \begin{pmatrix} 1 & 0 & \cdots & 0 & b \\ a & 1 & \cdots & & 0 \\ 0 & a & \ddots & \vdots & \vdots \\ \vdots & \vdots & \ddots & 1 & 0 \\ 0 & 0 & \cdots & a & 1 \end{pmatrix}$$

If we know how to compute  $A^{-1}$  and  $B^{-1}$ , computing  $Q_{ee}^{-1}$  is easy:

$$Q_{ee}^{-1} = \frac{1 + \gamma_5}{2} A^{-1} + \frac{1 - \gamma_5}{2} B^{-1}.$$

$\langle \text{Compute } Q_{ee}^{-1} \text{ part on the } s\text{-slice} \rangle \equiv$   
 $\langle \text{Compute } A^{-1}\psi \text{ on upper two components} \rangle$   
 $\langle \text{Compute } B^{-1}\psi \text{ on lower two components} \rangle$

If  $A = L_A R_A$ ,  $B = L_B R_B$ , where  $R_A$  and  $R_B$  are bidiagonal:

$$R_A = \begin{pmatrix} 1 & a & 0 & \cdots & 0 \\ 0 & 1 & a & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & & \cdots & 1 & a \\ 0 & 0 & \cdots & 0 & 1 \end{pmatrix} \quad R_B = \begin{pmatrix} 1 & 0 & \cdots & 0 & 0 \\ a & 1 & \cdots & & 0 \\ 0 & a & \ddots & \vdots & \vdots \\ \vdots & \vdots & \ddots & 1 & 0 \\ 0 & 0 & \cdots & a & 1 \end{pmatrix},$$

one can easily find

$$L_A = \begin{pmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 0 & \cdots & 0 \\ \vdots & & \ddots & & & \vdots \\ b & -ab & a^2b & -a^3b & \cdots & 1 + (-a)^{n-1}b \end{pmatrix} \quad L_B = \begin{pmatrix} 1 + (-a)^{n-1}b & (-a)^{n-2}b & \cdots & a^2b & -ab & b \\ 0 & 1 & 0 & \cdots & & 0 \\ \vdots & & \ddots & & & \vdots \\ 0 & \cdots & & & 0 & 1 \end{pmatrix}$$

In these terms,

$$Q_{ee}^{-1} = \frac{1 + \gamma_5}{2} R_A^{-1} L_A^{-1} + \frac{1 - \gamma_5}{2} R_B^{-1} L_B^{-1}.$$

$\langle \text{Compute } A^{-1}\psi \text{ on upper two components} \rangle \equiv$   
 $\langle \text{Compute } L_A^{-1} \text{ part} \rangle$   
 $\langle \text{Compute } R_A^{-1} \text{ part} \rangle$

$\langle \text{Compute } B^{-1}\psi \text{ on lower two components} \rangle \equiv$   
 $\langle \text{Compute } L_B^{-1} \text{ part} \rangle$   
 $\langle \text{Compute } R_B^{-1} \text{ part} \rangle$

Computing  $z^{(A)} = L_A^{-1}x$  and  $z^{(B)} = L_B^{-1}x$  is easy:

$$z_k^{(A)} = \begin{cases} \sum_{j=0}^{n-2} \frac{(-a)^j b}{1+(-a)^{n-1}b} x_j + \frac{1}{1+(-a)^{n-1}b} x_{n-1}, & \text{if } k = n-1 \\ x_k, & \text{otherwise} \end{cases}$$

$$z_k^{(B)} = \begin{cases} \frac{1}{1+(-a)^{n-1}b} x_0 + \sum_{j=1}^{n-1} \frac{(-a)^{n-1-j} b}{1+(-a)^{n-1}b} x_j, & \text{if } k = 0 \\ x_k, & \text{otherwise} \end{cases}$$

We can compute  $z$  *in situ*. Care should be taken, however, to use SSE in the sums.

```

⟨Compute  $L_A^{-1}$  part⟩≡
  zV = vhfzero; fx = ab_LA;
  for (int s = 0; s < S4_1; s++, fx = fx * va4) {
    VDiracFermion &rs = rx[s];
    ⟨Compute  $zV \leftarrow zV + fx * rx_{[s]}^{up}$ ⟩
  }
  {
    VDiracFermion &rs = rx[S4_1];
    fx.vput_3(c0);
    ⟨Compute  $zV \leftarrow zV + fx * rx_{[s]}^{up}$ ⟩
    for (int c = 0; c < 3; c++) {
      ⟨Compute wall value in zX...⟩

      zn = rs.v[0][c];
      zn.vput_3(zX0c);
      rs.v[0][c] = zn;

      zn = rs.v[1][c];
      zn.vput_3(zX1c);
      rs.v[1][c] = zn;
    }
  }

```

To avoid strange things gcc does when SSE data is declared local to a block, we place all such variables on the function level:

```

⟨QQxx locals⟩≡
  vreal fx;
  VDiracFermion zV;
  vcomplex zn, z1, z2, z3;
  complex zX0c, zX1c;

```

This piece is used twice: once in the loop over  $L_s$ , and the second time after correcting  $s_3$ :

```

⟨Compute  $zV \leftarrow zV + fx * rx_{[s]}^{up}$ ⟩≡
  for (int c = 0; c < 3; c++) {
    zV.v[0][c] = zV.v[0][c] + fx * rs.v[0][c];
    zV.v[1][c] = zV.v[1][c] + fx * rs.v[1][c];
  }

```

By now, we have four partial sums which must be combined into  $z_{n-1}$ :

```

⟨Compute wall value in zX...⟩≡
  zX0c = zV.v[0][c].sum();
  zX1c = zV.v[1][c].sum();

```

Computing  $L_B^{-1}$  differs fro  $L_A^{-1}$  only in the direction of the loop over the fifth dimension and change from the upper to the lower half of fermion indices.

```

⟨Compute  $L_B^{-1}$  part⟩≡
    zV = vhfzero; fx = ab_LB;
    for (int s = S4; --s; fx = fx * va4) {
        VDiracFermion &rs = rx[s];
        ⟨Compute  $zV \leftarrow zV + fx * rx_{[s]}^{down}$ ⟩
    }
    {
        VDiracFermion &rs = rx[0];
        fx.vput_0(c0);
        ⟨Compute  $zV \leftarrow zV + fx * rx_{[s]}^{down}$ ⟩
        for (int c = 0; c < 3; c++) {
            ⟨Compute wall value in zX...⟩

            zn = rs.v[2][c];
            zn.vput_0(zX0c);
            rs.v[2][c] = zn;

            zn = rs.v[3][c];
            zn.vput_0(zX1c);
            rs.v[3][c] = zn;
        }
    }
}

```

This piece is used twice: once in the loop over  $L_s$ , and the second time after correcting  $s_0$ :

```

⟨Compute  $zV \leftarrow zV + fx * rx_{[s]}^{down}$ ⟩≡
    for (int c = 0; c < 3; c++) {
        zV.v[0][c] = zV.v[0][c] + fx * rs.v[2][c];
        zV.v[1][c] = zV.v[1][c] + fx * rs.v[3][c];
    }
}

```

One can compute  $y^{(A)} = R_A^{-1}x$  and  $y^{(B)} = R_B^{-1}x$  iteratively:

$$\begin{aligned}
 y_k^{(A)} &= \begin{cases} x_k, & \text{if } k = n-1 \\ x_k - ay_{k+1}^{(A)}, & \text{otherwise} \end{cases} \\
 y_k^{(B)} &= \begin{cases} x_0, & \text{if } k = 0 \\ x_k - ay_{k-1}^{(B)}, & \text{otherwise} \end{cases}
 \end{aligned}$$

We need one last step to make computation of  $R^{-1}$  vector-friendly. Unrolling iterative definitions four times, one gets:

$$\begin{aligned}
 y_k^{(A)} &= \begin{cases} x_k, & \text{if } k = n-1 \\ x_k - ay_{k+1}^{(A)}, & \text{if } n-4 \leq k \leq n-2 \\ x_k - ax_{k+1} + a^2x_{k+2} - a^3x_{k+3} + a^4y_{k+4}^{(A)}, & \text{otherwise} \end{cases} \\
 y_k^{(B)} &= \begin{cases} x_0, & \text{if } k = 0 \\ x_k - ay_{k-1}^{(B)}, & \text{if } 1 \leq k \leq 3 \\ x_k - ax_{k-1} + a^2x_{k-2} - a^3x_{k-3} + a^4y_{k-4}^{(B)}, & \text{otherwise} \end{cases}
 \end{aligned}$$

If we extend  $x$  by setting  $x_k = 0$  iff  $k < 0$  or  $k \geq n$  and also set  $y_k^{(A)} = 0$  for  $k \geq n$  and  $y_k^{(B)} = 0$  for  $k < 0$ , we do not need special cases on the boundaries.

```

⟨Init out of bound x and y⟩≡
    xOut = vhfzero;
    yOut = vhfzero;

```

Again, it is better to place xOut and yOut on the function level:

```

⟨QQxx locals⟩+≡
    VDiracFermion xOut;
    VDiracFermion yOut;

```



With such an extended  $x$  and  $y$  we can use the following formulae:

$$\begin{aligned} y_k^{(A)} &= x_k - ax_{k+1} + a^2x_{k+2} - a^3x_{k+3} + a^4y_{k+4}^{(A)} \\ y_k^{(B)} &= x_k - ax_{k-1} + a^2x_{k-2} - a^3x_{k-3} + a^4y_{k-4}^{(B)} \end{aligned}$$

```

⟨Compute  $R_A^{-1}$  part⟩≡
  ⟨Init out of bound  $x$  and  $y$ ⟩
  for (int s = S4; s--;) {
    VDiracFermion &rs = rx[s];
    for (int c = 0; c < 3; c++) {
      ⟨Compute  $y_{k,[0]}^{(A)}⟩$ 
      ⟨Compute  $y_{k,[1]}^{(A)}⟩$ 
    }
  }

⟨Compute  $y_{k,[0]}^{(A)}⟩$ ≡
  zn = rs.v[0][c];
  z1 = zn.shift_down1(xOut.v[0][c]);
  z2 = zn.shift_down2(xOut.v[0][c]);
  z3 = zn.shift_down3(xOut.v[0][c]);
  rs.v[0][c] = zn - va1 * z1 + va2 * z2 - va3 * z3 + va4 * yOut.v[0][c];
  yOut.v[0][c] = rs.v[0][c];
  xOut.v[0][c] = zn;

⟨Compute  $y_{k,[1]}^{(A)}⟩$ ≡
  zn = rs.v[1][c];
  z1 = zn.shift_down1(xOut.v[1][c]);
  z2 = zn.shift_down2(xOut.v[1][c]);
  z3 = zn.shift_down3(xOut.v[1][c]);
  rs.v[1][c] = zn - va1 * z1 + va2 * z2 - va3 * z3 + va4 * yOut.v[1][c];
  xOut.v[1][c] = zn;
  yOut.v[1][c] = rs.v[1][c];

⟨Compute  $R_B^{-1}$  part⟩≡
  ⟨Init out of bound  $x$  and  $y$ ⟩
  for (int s = 0; s < S4; s++) {
    VDiracFermion &rs = rx[s];
    for (int c = 0; c < 3; c++) {
      ⟨Compute  $y_{k,[2]}^{(B)}⟩$ 
      ⟨Compute  $y_{k,[3]}^{(B)}⟩$ 
    }
  }

⟨Compute  $y_{k,[2]}^{(B)}⟩$ ≡
  zn = rs.v[2][c];
  z1 = xOut.v[2][c].shift_up1(zn);
  z2 = xOut.v[2][c].shift_up2(zn);
  z3 = xOut.v[2][c].shift_up3(zn);
  rs.v[2][c] = zn - va1 * z1 + va2 * z2 - va3 * z3 + va4 * yOut.v[2][c];
  yOut.v[2][c] = rs.v[2][c];
  xOut.v[2][c] = zn;

⟨Compute  $y_{k,[3]}^{(B)}⟩$ ≡
  zn = rs.v[3][c];
  z1 = xOut.v[3][c].shift_up1(zn);
  z2 = xOut.v[3][c].shift_up2(zn);
  z3 = xOut.v[3][c].shift_up3(zn);
  rs.v[3][c] = zn - va1 * z1 + va2 * z2 - va3 * z3 + va4 * yOut.v[3][c];
  yOut.v[3][c] = rs.v[3][c];
  xOut.v[3][c] = zn;

```

The only part left is computing lattice-independant values for the fifth dimension.

```

⟨Compute constant values for  $Q_{ee}^{-1}$ ⟩≡
    real c0 = 1./(1+b*pow(a,S4*4-1));
    vreal va1(a);
    vreal va2(a*a);
    vreal va3(a*a*a);
    vreal va4(a*a*a*a);
    vreal ab_LA(c0*b, -a*c0*b, a*a*c0*b, -a*a*a*c0*b);
    vreal ab_LB(-a*a*a*c0*b, a*a*c0*b, -a*c0*b, c0*b);
    vreal vzero(0);
    VDiracFermion vhfzero;
    for (int d = 0; d < 4; d++) {
        for (int c = 0; c < 3; c++) {
            vhfzero.v[d][c].re = vzero;
            vhfzero.v[d][c].im = vzero;
        }
    }

```

This completes computation of  $Q_{ee}^{-1}x$ .

### 3 INTERFACE

It is convenient to choose such a basis of Clifford algebra that  $\gamma_5$  is diagonal—we can use  $\gamma$ -matrices from the previous note.

```

⟨kostas.hh⟩≡
    #ifndef KOSTAS_HH
    #define KOSTAS_HH
    #include "qcd.hh"
    namespace QCDSSE {
        ⟨Gauge Fields⟩
        ⟨Dirac Fermions⟩

        ⟨QCD classes⟩
    };
    #endif

```

We can borrow SU3 and VSU3 from `sse.nw`:

```

⟨Gauge Fields⟩≡
    struct SU3 {
        complex v[3][3];
    };

```

When applying the parallel transport to fermions, we need to fill SSE 4-vectors with the same values. Because gcc does register allocation for us, we introduce VSU3 structure:

```

⟨Gauge Fields⟩+≡
    struct VSU3 {
        vcomplex v[3][3];
        ⟨Vector Gauge Field constructors⟩
    };

```

We need an empty constructor for VSU3 because gcc is not very smart.

```

⟨Vector Gauge Field constructors⟩≡
    inline VSU3() {}

```

Five dimensional fermions are packaged along the  $s$ -direction

```

⟨Dirac Fermions⟩≡
    struct VDiracFermion {
        vcomplex v[4][3];
    };

```

Since we waste memory bandwidth on  $(1 \pm \gamma_\mu)$  projected fermions, let us make a data type for them:

$\langle \text{Dirac Fermions} \rangle + \equiv$

```
struct VHalfFermion {
    vcomplex v[2][3];
};
```

QCD interface is quite similar to the original SSE version

$\langle \text{QCD classes} \rangle \equiv$

```
class GaugeField {
    SU3 *v;
public:
    GaugeField(SU3 *r): v(r) {}
    SU3 &operator[](int i) { return v[i]; }
};

class GaugeField4d {
    SU3 *v;
public:
    GaugeField4d(SU3 *r): v(r) {}
    GaugeField operator[](int i) const { return GaugeField(v + 4 * i); }
};
```

For Dirac fermions, on the other hand, it is convenient to have 1- and 5-dimensional classes:

$\langle \text{QCD classes} \rangle + \equiv$

```
class DiracFermion1d {
    VDiracFermion *f;
public:
    DiracFermion1d(): f(0) {}
    DiracFermion1d(VDiracFermion *x): f(x) {}
    VDiracFermion &operator[](int i) { return f[i]; }
};

class DiracFermion5d {
    VDiracFermion *f;
    int S4;
public:
    DiracFermion5d(VDiracFermion *x, int s4): f(x), S4(s4) {}
    DiracFermion1d operator[](int i) const { return DiracFermion1d(f + S4 * i); }
};
```

As if more code is better, we need to build 5-d lattices of half fermions. Of course, one can pretend to do a better job with templates, but the code compiles slowly already.

$\langle \text{QCD classes} \rangle + \equiv$

```
class HalfFermion1d {
    VHalfFermion *f;
public:
    HalfFermion1d(): f(0) {}
    HalfFermion1d(VHalfFermion *x): f(x) {}
    VHalfFermion &operator[](int i) { return f[i]; }
};

class HalfFermion5d {
    VHalfFermion *f;
    int S4;
public:
    HalfFermion5d(): f(0), S4(0) {}
    HalfFermion5d(VHalfFermion *x, int s4): f(x), S4(s4) {}
    HalfFermion1d operator[](int i) const { return HalfFermion1d(f + S4 * i); }
};
```

For the sake of exposition, let us collect all pieces describing lattice geometry into one class. It is likely, that an application will have only one variable of class `Lattice5d`, but what the heck.

```

⟨QCD classes⟩+=
class Lattice5d {
    int X, Y, Z, T, S4, S4_1;
    int XYZT2;

    struct step {
        int d[4];
    };
    struct rb_lattice {
        step *Hup;
        step *Hdown;
        step *Fdown;
        step *Fup;
        step *Udown;
        int *Uup;
    };
    HalfFermion5d proj[8];

    rb_lattice eo;
    void QQxx(DiracFermion5d &result,
              const GaugeField4d &U,
              const DiracFermion5d &psi,
              double a, double b,
              const rb_lattice &xx);
    int full_lattice(int x, int y, int z, int t);
    int even_lattice(int x, int y, int z, int t);
    int odd_lattice(int x, int y, int z, int t);
    HalfFermion5d create_halffermion(int n);
public:
    Lattice5d(int x, int y, int z, int t, int s);
    ~Lattice5d();
    DiracFermion5d create_fermion(void);
    GaugeField4d create_gauge(void);
    void Qee1Qeo(DiracFermion5d &result,
                 const GaugeField4d &U,
                 const DiracFermion5d &psi,
                 double a, double b) { QQxx(result, U, psi, a, b, eo); }
    int QQOps(void);
};

```

### 3.1 Field Allocators

In its present form, gcc does not perform `new` properly on `VREAL` objects. For this reason, we implement two methods in `[Lattice5d]` responsible for allocation of gauge fields and five-dimensional fermions respectively.

```

⟨QCD methods⟩=

GaugeField4d
Lattice5d::create_gauge(void)
{
    SU3 *v = new SU3[XYZT2 * 2 * 4];

    ⟨Initialize Gauge Field⟩
    return v;
}

```

For now, we fill gauge field with random numbers:

```

<Initialize Gauge Field>≡
    real *f = (real *)v;
    for (int i = sizeof(SU3) * 4 * 2 * XYZT2 / sizeof(real); i--;) {
        f[i] = rand() / (double)RAND_MAX;
    }

```

Equally simple is allocating a fresh red/black sublattice of VDiracFermion. Unfortunately, gcc's new is broken, we need to align SSE data manually.

```

<QCD methods>+≡
    DiracFermion5d
    Lattice5d::create_fermion(void)
    {
        char *ptr = new char[sizeof (VDiracFermion) * (XYZT2 * S4 + 1)];
        unsigned long v = (unsigned long)ptr;
        unsigned long v_aligned = (v + 15) & ~15;

        <Initialize 5d Fermion>
        return DiracFermion5d((VDiracFermion *)v_aligned, S4);
    }

```

Fermion field is also initialized with random numbers:

```

<Initialize 5d Fermion>≡
    real *f = (real *)v_aligned;
    for (int i = sizeof(VDiracFermion) / sizeof(*f) * XYZT2 * S4; i--;) {
        f[i] = rand() / (double)RAND_MAX;
    }

```

In a single-processor case we do not need extra space for receive buffers in half-fermions. However, let us pass the number of needed elements as an argument to the allocator:

```

<QCD methods>+≡
    HalfFermion5d
    Lattice5d::create_half fermion(int count)
    {
        char *ptr = new char[sizeof (VHalfFermion) * (count * S4 + 1)];
        unsigned long v = (unsigned long)ptr;
        unsigned long v_aligned = (v + 15) & ~15;

        return HalfFermion5d((VHalfFermion *)v_aligned, S4);
    }

```

In the Lattice5d object we store all information needed to navigate through the lattice and create lattice objects (e.g., gauge and fermion fields)

```

<QCD methods>+≡
    Lattice5d::Lattice5d(int x, int y, int z, int t, int s)
    {
        <Compute Lattice5d sizes>
        <Create eo neighbor tables>
        <Fill neighbor tables values>
        <Create half fermion buffers>
    }

```

This version of <Create half fermion buffers> does not have space for receive buffers. In the network version more space must be allocated here

```

<Create half fermion buffers>≡
    for (int i = 0; i < 8; i++)
        proj[i] = create_half fermion(XYZT2 * S4);

```

Remember that four-vectors are aligned along the s-direction and even/odd is done in 4-d slices:

```

<Compute Lattice5d sizes>≡
    X = x; Y = y; Z = z; T = t; S4 = s/4; S4_1 = S4 - 1;
    XYZT2 = X * Y * Z * T / 2;

```

We only compute `eo` tables here.

*⟨Create eo neighbor tables⟩*≡

```
eo.Hup = new step[XYZT2];
eo.Hdown = new step[XYZT2];
eo.Fdown = new step[XYZT2];
eo.Fup = new step[XYZT2];
eo.Udown = new step[XYZT2];
eo.Uup = new int[XYZT2];
```

To fill the values in the neighbor tables, start with walking over four dimensions

*⟨Fill neighbor tables values⟩*≡

```
for (int x = 0; x < X; x++) {
    for (int y = 0; y < Y; y++) {
        for (int z = 0; z < Z; z++) {
            int p = (x + y + z) & 1;
            for (int t = p; t < T; t += 2) {
                int i = even_lattice(x,y,z,t);
                ⟨Compute eo[i] elements for (x,y,z,t)⟩
            }
        }
    }
}
```

Since we have both linear and four-dimensional addresses of the current point, computing the neighbors is easy:

*⟨Compute eo[i] elements for (x,y,z,t)⟩*≡

```
eo.Uup[i] = full_lattice(x,y,z,t);
⟨Compute eo.Udown[i].d⟩
⟨Compute eo.Fup[i].d⟩
⟨Compute eo.Fdown[i].d⟩
⟨Compute eo.Hup[i].d⟩
⟨Compute eo.Hdown[i].d⟩
```

*⟨Compute eo.Udown[i].d⟩*≡

```
eo.Udown[i].d[0] = full_lattice(x-1,y,z,t);
eo.Udown[i].d[1] = full_lattice(x,y-1,z,t);
eo.Udown[i].d[2] = full_lattice(x,y,z-1,t);
eo.Udown[i].d[3] = full_lattice(x,y,z,t-1);
```

Parts dealing with destination of  $\gamma$ -projections unvert the direction on the lattice: they are addresses of *destinations*.

*⟨Compute eo.Fup[i].d⟩*≡

```
eo.Fup[i].d[0] = odd_lattice(x-1,y,z,t);
eo.Fup[i].d[1] = odd_lattice(x,y-1,z,t);
eo.Fup[i].d[2] = odd_lattice(x,y,z-1,t);
eo.Fup[i].d[3] = odd_lattice(x,y,z,t-1);
```

*⟨Compute eo.Fdown[i].d⟩*≡

```
eo.Fdown[i].d[0] = odd_lattice(x+1,y,z,t);
eo.Fdown[i].d[1] = odd_lattice(x,y+1,z,t);
eo.Fdown[i].d[2] = odd_lattice(x,y,z+1,t);
eo.Fdown[i].d[3] = odd_lattice(x,y,z,t+1);
```

Life is simple until one has to think about communications. For local version, it is enough to put identity maps into `eo.Hup` and `eo.Hdown`:

*⟨Compute eo.Hup[i].d⟩*≡

```
eo.Hup[i].d[0] = i;
eo.Hup[i].d[1] = i;
eo.Hup[i].d[2] = i;
eo.Hup[i].d[3] = i;
```

*⟨Compute eo.Hdown[i].d⟩*≡

```
eo.Hdown[i].d[0] = i;
eo.Hdown[i].d[1] = i;
eo.Hdown[i].d[2] = i;
eo.Hdown[i].d[3] = i;
```

Three converters from 4-d lattice address to 1-d memory address:

$\langle QCD\ methods \rangle + \equiv$

```
int
Lattice5d::full_lattice(int x, int y, int z, int t)
{
    if (x < 0) x += X; if (x >= X) x -= X;
    if (y < 0) y += Y; if (y >= Y) y -= Y;
    if (z < 0) z += Z; if (z >= Z) z -= Z;
    if (t < 0) t += T; if (t >= T) t -= T;
    return t + T * (z + Z * (y + Y * x));
}
```

$\langle QCD\ methods \rangle + \equiv$

```
int
Lattice5d::even_lattice(int x, int y, int z, int t)
{
    return full_lattice(x,y,z,t)/2;
}
```

$\langle QCD\ methods \rangle + \equiv$

```
int
Lattice5d::odd_lattice(int x, int y, int z, int t)
{
    return full_lattice(x,y,z,t)/2;
}
```

Finally, we need to cleanup space used by the tables when Lattice5d is freed:

$\langle QCD\ methods \rangle + \equiv$

```
Lattice5d::~~Lattice5d()
{
    delete eo.Fdown;
    delete eo.Fup;
    delete eo.Udown;
    delete eo.Uup;
    delete eo.Hup;
    delete eo.Hdown;
}
```

## 4 THE BEEF

Armed with all the experience of SSE magic, we boldly go ahead:

$\langle kostas.cc \rangle \equiv$

```
#include <stdlib.h>
#include <math.h>
#include "kostas.hh"
using namespace QCDSSE;
 $\langle QCD\ methods \rangle$ 
```

We traditionally start with an implementation of the preconditioned Dirak operator.

```

<QCD methods>+=
void
Lattice5d::QQxx(DiracFermion5d &result,
                const GaugeField4d &U,
                const DiracFermion5d &psi,
                double a, double b,
                const rb_lattice &xx)
{
    <QQxx locals>

    <Compute constant values for  $Q_{ee}^{-1}$ >
    <Collect  $\gamma$ -projections to degrade performance>
    <Send & Receive>
    <Complete  $Q_{eo}$  computation and apply  $Q_{ee}^{-1}$  to the result>
}

```

First, we project the whole 5-d fermion field in eight ways and store results into temporaries. This is done with data reshuffling needed to collect continuous communication buffers for QMP. Reshuffling itself is not a limiting operation, however, significant extra memory bus traffic is generated at this stage.

```

<Collect  $\gamma$ -projections to degrade performance>=
for (int xyzt = XYZT2; xyzt--;) {
    <Extract 1-d addresses for  $\gamma$ -projections>
    for (int s = 0; s < S4; s++) {
        <Compute  $\gamma$ -projections and store the results>
    }
}

<Compute  $\gamma$ -projections and store the results>=
<Construct neighbors references>
for (int c = 0; c < 3; c++) {
    <Project  $\gamma_1$  upward link>
    <Project  $\gamma_1$  downward link>
    <Project  $\gamma_2$  upward link>
    <Project  $\gamma_2$  downward link>
    <Project  $\gamma_3$  upward link>
    <Project  $\gamma_3$  downward link>
    <Project  $\gamma_4$  upward link>
    <Project  $\gamma_4$  downward link>
}

```

Local part of  $Q_{ee}^{-1}Q_{eo}\psi$  does not change much:

```

<Complete  $Q_{eo}$  computation and apply  $Q_{ee}^{-1}$  to the result>=
for (int xyzt = XYZT2; xyzt--;) {
    <Extract 1-d addresses for  $Q_{eo}$  and  $Q_{ee}^{-1}$ >
    <Build SSE SU(3) and HalfFermion1d objects>
    <Compute  $Q_{eo}$  part on the s-slice>
    <Compute  $Q_{ee}^{-1}$  part on the s-slice>
}

```



The Q-code has grown too large to fit into the trace cache. We need to compact the inner loop. (Such a change seems not to effect performance of P4, by the way). We pack all VSU3 into an array, so that all sixteen  $SU(3)$  multiplications can be performed in a loop.

```

<Build SSE SU(3) and HalfFermion1d objects>≡
  GaugeField Uup = U[xx.Uup[xyzt]];
  for (int d = 0; d < 4; d++) {
    <Compute HalfFermion1d for d direction>
    SU3 &Udown = U[xx.Udown[xyzt].d[d]][d];
    for (int a = 0; a < 3; a++) {
      for (int b = 0; b < 3; b++) {
        V[d*2+0].v[a][b] = vcomplex(Uup[d].v[a][b].re, Uup[d].v[a][b].im);
        V[d*2+1].v[a][b] = vcomplex(Udown.v[b][a].re, -Udown.v[b][a].im);
      }
    }
  }

```

Unfortunately, gcc does something quite unexplicable with some block-level declarations. To avoid run-time overhead, all SSE variables are declared at the function level in QQxx:

```

<QQxx locals>+≡
  VSU3 V[8];

```

With all gauge fields brought into L1 cache and converted into SSE vectors, we are ready to compute an  $s$ -slice of  $Q_{eo}$ .

```

<Compute Qeo part on the s-slice>≡
  for (int s = 0; s < S4; s++) {
    <Multiply by V>
    <Compute  $\gamma$ -unprojections and sum the results>
  }

```

To prepare for matrix multiplication,  $\gamma$ -projections are combined with collecting the fermion pieces into an L1 array.

```

<QQxx locals>+≡
  VHalfFermion g[8];

```

Here is a major space saver. By the clever tricks above, all pieces are in L1 and we can do the multiplications in a neat loop.

```

<Multiply by V>≡
  for (int n = 0; n < 8; n++) {
    <Get half-fermion reference into h>
    <Get gauge field reference into v>
    <Get result reference into gg>
    for (int c = 0; c < 3; c++) {
      <Compute  $gg_{0c}^n$  and  $gg_{1c}^n$ >
    }
  }

```

```

<Compute  $gg_{0c}^n$  and  $gg_{1c}^n$ >≡
  gg.v[0][c] = v.v[c][0]*h.v[0][0]+v.v[c][1]*h.v[0][1]+v.v[c][2]*h.v[0][2];
  gg.v[1][c] = v.v[c][0]*h.v[1][0]+v.v[c][1]*h.v[1][1]+v.v[c][2]*h.v[1][2];

```

It's better to assume that constant expression optimization does not work. Hence, all addresses are computed outside the color loop:

```

<Get half-fermion reference into h>≡
  VHalfFermion &h = hf[n][s];

<Get gauge field reference into v>≡
  VSU3 &v = V[n];

```

```

<Get result reference into gg>≡
  VHalfFermion &gg = g[n];

```

```

<Compute HalfFermion1d for d direction>≡
  hf[2*d+0] = proj[2*d+0][xx.Hup[xyzt].d[d]];
  hf[2*d+1] = proj[2*d+1][xx.Hdown[xyzt].d[d]];

```

```

<QQxx locals>+≡
  HalfFermion1d hf[8];

```

The final step in  $Q_{eo}$  could also be compacted. One peculiarity here is that we start collecting results from  $(1 + \gamma_2)$  because it saves us a few additions.

```

⟨Compute  $\gamma$ -unprojections and sum the results⟩≡
  VDiracFermion &rs = rx[s];
  for (int c = 0; c < 3; c++) {
    ⟨Unproject  $\gamma_2$  upward link⟩
    ⟨Unproject and accumulate  $\gamma_2$  downward link⟩
    ⟨Unproject and accumulate  $\gamma_1$  upward link⟩
    ⟨Unproject and accumulate  $\gamma_1$  downward link⟩
    ⟨Unproject and accumulate  $\gamma_3$  upward link⟩
    ⟨Unproject and accumulate  $\gamma_3$  downward link⟩
    ⟨Unproject and accumulate  $\gamma_4$  upward link⟩
    ⟨Unproject and accumulate  $\gamma_4$  downward link⟩
  }

```

This simply helps gcc in its quest for optimization

```

⟨Extract 1-d addresses for  $Q_{eo}$  and  $Q_{ee}^{-1}$ ⟩≡
  DiracFermion1d rx(result[xyzt]);

```

Finally, let us count the floating point operations.

$\gamma$ -projections	$2(\text{complex}) \times 3(\text{colors}) \times 2(\text{half fermions}) \times 8(\text{directions}) \times 1(\text{add})$	=	96
$\gamma$ -unprojections	$2(\text{complex}) \times 3(\text{colors}) \times 4(\text{full fermions}) \times 7(\text{directions}) \times 1(\text{add})$	=	168
Gauge multiplications	$2(\text{complex}) \times 3(\text{colors}) \times 2(\text{half fermions}) \times 8(\text{directions}) \times (6(\text{multiply}) + 5(\text{add}))$	=	1056
Applying $L_A^{-1}$ and $L_B^{-1}$	$2(L_A^{-1} \text{ and } L_B^{-1}) \times 2(\text{complex}) \times 3(\text{colors}) \times 2(\text{half fermions}) \times (1(\text{multiply}) + 1(\text{add}))$	=	48
Applying $R_A^{-1}$ and $R_B^{-1}$	$2(R_A^{-1} \text{ and } R_B^{-1}) \times 2(\text{complex}) \times 3(\text{colors}) \times 2(\text{half fermions}) \times (4(\text{multiply}) + 4(\text{add}))$	=	192
Total per site		=	1560

thus,

```

⟨QCD methods⟩+≡
  int
  Lattice5d::QQOps(void)
  {
    return XYZT2 * S4 * 4 * 1560;
  }

```

## 5 TEST CODE

The test is to loop  $K_{eo}$  enough time to get an estimate of performance.

```
<k-main.cc>≡
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>
#include <sys/resource.h>
#include <unistd.h>
#include "kostas.hh"

int
main(int argc, char *argv[]) {
    using namespace QCDSSSE;
    <check arguments>
    <create dynamic objects>
    struct rusage us0, us1;
    struct timeval t0, t1;
    getrusage(RUSAGE_SELF, &us0);
    <perform SSE operations>
    getrusage(RUSAGE_SELF, &us1);
    t0 = us0.ru_utime;
    t1 = us1.ru_utime;
    <show time elapsed and performance>

    return 0;
}
```

Lattice size and number of iterations are arguments of `main()`:

```
<check arguments>≡
if (argc != 7) {
    fprintf(stderr, "usage: sse X Y Z T S iter\n");
    return 1;
}
```

From X, Y, Z and T we only require to be even and positive:

```
<check arguments>+≡
int X = atoi(argv[1]);
if ((X <= 0) || (X & 1 != 0)) {
    fprintf(stderr, "X must be even positive. (it is %d)\n", X);
    return 1;
}
```

```
<check arguments>+≡
int Y = atoi(argv[2]);
if ((Y <= 0) || (Y & 1 != 0)) {
    fprintf(stderr, "Y must be even positive. (it is %d)\n", Y);
    return 1;
}
```

```
<check arguments>+≡
int Z = atoi(argv[3]);
if ((Z <= 0) || (Z & 1 != 0)) {
    fprintf(stderr, "Z must be even positive. (it is %d)\n", Z);
    return 1;
}
```

```

⟨check arguments⟩+=
    int T = atoi(argv[4]);
    if ((T <= 0) || (T & 1 != 0)) {
        fprintf(stderr, "T must be even positive. (it is %d)\n", T);
        return 1;
    }

```

However, S must be a multiple of 8:

```

⟨check arguments⟩+=
    int S = atoi(argv[5]);
    if ((S <= 4) || (S & 3 != 0)) {
        fprintf(stderr,
            "S must be positive multiple of 4 and at least 8 (it is %d)\n",
            S);
        return 1;
    }

```

Number of iteration is simply taken from the sixth argument:

```

⟨check arguments⟩+=
    int count = atoi(argv[6]);

```

Next, we create Lattice5d object that will handle all other memory allocations.

```

⟨create dynamic objects⟩=
    Lattice5d Lattice(X, Y, Z, T, S);

```

We need one gauge field on Lattice:

```

⟨create dynamic objects⟩+=
    GaugeField4d U = Lattice.create_gauge();

```

and two Dirac fermions (even and odd sublattices)

```

⟨create dynamic objects⟩+=
    DiracFermion5d phi = Lattice.create_fermion();
    DiracFermion5d psi = Lattice.create_fermion();

```

Now we have all the pieces to compute  $\phi = K_{eo}\psi$ . Values of  $a = 2/M_0$  and  $b = -2m_f/M_0$  are not important for performance measurements:

```

⟨perform SSE operations⟩=
    for (int i = count; i--;) {
        Lattice.Qee1Qeo(phi, U, psi, 0.1, -0.01);
    }

```

Computing elapsed time is easy

```

⟨show time elapsed and performance⟩=
    double dt = t1.tv_sec - t0.tv_sec + 10e-6*(t1.tv_usec - t0.tv_usec);

```

However, the elapsed time may be too short to compute performance. Check of overflow here to avoid embarrassment

```

⟨show time elapsed and performance⟩+=
    if (dt > 0) {
        printf("Performance %g Mflops/sec. Lattice %d %d %d %d %d ."
            " %d Iterations. %g total seconds\n",
            (double)count * Lattice.QQOps() / dt / 1e6,
            X, Y, Z, T, S, count, dt);
    } else {
        printf("*** Qee1Qeo ran too fast. Try increasing count\n");
        return 1;
    }

```

## 6 THINGS TO DO FOR QMP

This is a placeholder for the communication part.

```

⟨Send & Receive⟩=
    // Send and receive stuff in all directions.

```

We also need some changes to other pieces:

1.  $\langle \text{Compute } \mathbf{eo.Fup}[i].\mathbf{d} \rangle$  and  $\langle \text{Compute } \mathbf{eo.Fdown}[i].\mathbf{d} \rangle$  need to collect boundaries into continuous buffers for QMP send.
2.  $\langle \text{Compute } \mathbf{eo.Hup}[i].\mathbf{d} \rangle$  and  $\langle \text{Compute } \mathbf{eo.Hdown}[i].\mathbf{d} \rangle$  must use the receive buffers the data on the boundary. They are no longer identity maps for distributed dimensions.
3. In  $\langle \text{Create half fermion buffers} \rangle$  more space should be allocated to allow receive buffers addressed as offsets in `proj`.
4. Allocators for SSE dynamical data must store results of `new` to allow for memory cleanup in the `Lattice5d::~~Lattice5d()`.
5. Namespace and datatype conventions should agree with the QDP++ structure for proper Level 3 integration.