Automated Performance Analysis and Tuning through IBM HPCST

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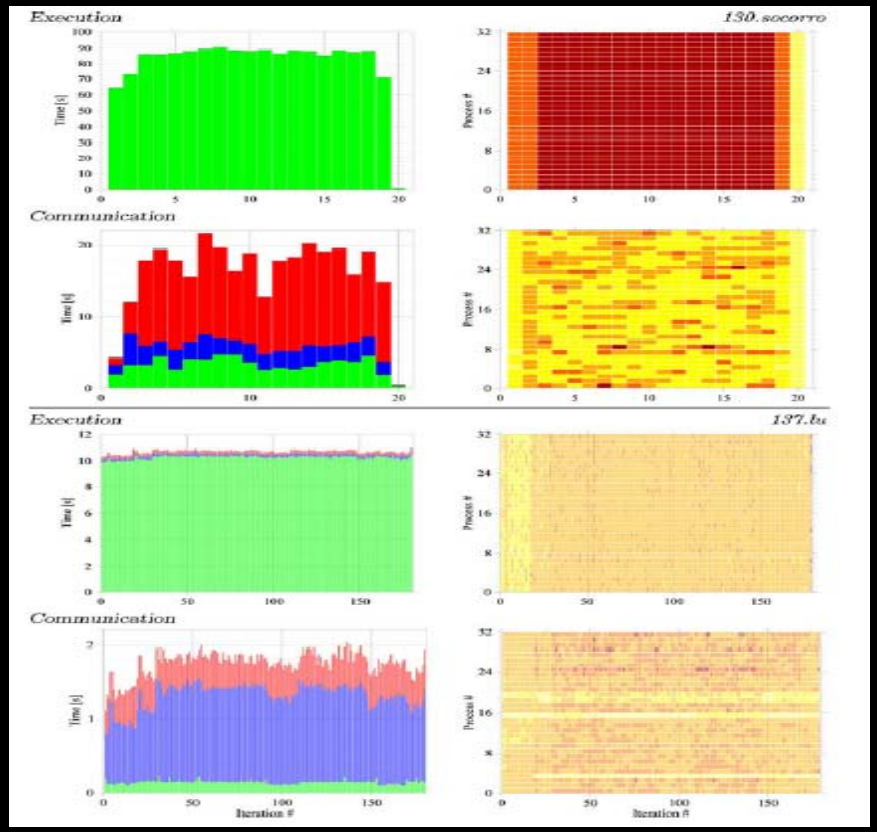
Background and motivation

- Quite some performance tools but few are widely accepted (observation at Watson and Pougkeepsie)
  - Profiling {Graham et al 82}
  - Performance counters
  - MPI tracing
- Addresses generic and pervasive problems with performance tuning; to improve productivity
  - Increasingly complex architectures
  - New science and applications
  - New programming models and languages
- Current practice is manual and labor intensive
  - Compiler has yet to catch up especially for news apps on new HPC platforms
  - Impossible to always produce optimal or near optimal solution
  - Many aspects of computing are evolving fast (at least at this time)
  - Domain specific knowledge
- Tuning is still a daunting task with different characteristics for different dimensions

Current efforts on analysis and tuning

- Feedback directed compiler optimization
  - limited, closed, compiler centric
- "Traditional" performance tools
  - Focuses mostly on instrumentation, tracing, profiling and presenting data
  - Not much tuning
  - Few interactions with the compiler
- Auto-tuners for libraries (e.g., ATLAS, SPIRAL)
  - Well-defined problems, small kernels, with limited parameter space
- Machine-learning based approaches
  - Training
  - Model unclear

Thousands of words

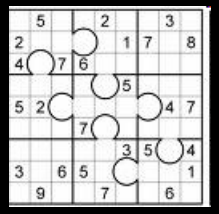


Our approach

- Automate or provide facilities to help semi-automate analysis and tuning
- Provide an open framework to draw on the expertise of the community
- Address multi dimensions of performance problems
  - CPU, memory, communication, I/O, etc
- Closer integration with compiler
- Knowledge-centric approach
- Support for PGAS languages

Key Questions

- What is a bottleneck
- Where is the bottleneck (hotspots)
- What are the possible solutions to a bottleneck
- What are the parameters to the solutions
- What are the impact of the solutoins



Bottleneck detection

- Rely on expert knowledge
- Components
  - Rule-based database, rules appear as logical expressions
  - Performance metrics are the basic components to construct a rule on
  - Modules are responsible to collect the metrics
  - Scheduler for scheduling the collection of metrics
    - Accuracy
    - Time

Solution determination and implementation

- Key components
  - Solution Database
  - Solution parameters discovery
  - Legality check
  - Performance Estimation
    - Detecting better solutions
  - Criteria
    - Improvement
    - Code impact
  - Implementation engine

Bottleneck rules

- OpenMPOverhead; 0 0 0 0 1; too much runtime overhead, not worth parallelizing the loop; MAX(PercentOverhead) > 50
- Latesender (wrong order from different source) waiting time detected; 0 0 0 1 0;Wrong order situation due to messages received from different sources;mpi_lswo_different > 1.0
- NotVectorized;1 0 0 0 0;loop not vectorized and vectorization could help;ndivides>0 and PM_CMPLU_STALL_FPU > (0.1*PM_RUN_CYC) and compiler_vectorized<1
- DcacheMiss; 1 0 0 0 0; cycles wasted due to stalls (D-cache miss, ERAT, FXU, FPU stalls); (PM_RUN_CYC - (PM_GCT_EMPTY_CYC + PM_GRP_CMPL)) > 0.1*PM_RUN_CYC

$$PM\_CMPLU\_STALL\_LSU/PM\_CYC > \alpha \;\&\&$$
$$SA\_STRIDE\_ONE\_ACCESS\_RATE \leq \beta \;\&\&$$
$$SA\_REGULAR\_ACCESS\_RATE(n) > SA\_STRIDE\_ONE\_ACCESS\_RATE + \gamma$$

$$\#divides > 0 \;\&\&\; \frac{PM\_STALL\_FPU}{PM\_RUN\_CYC} > t \;\&\&\; vectorized = 0$$

Sample bottlenecks discovered with integrated external tools

- Latesender waiting time detected, Time a receiving process is waiting for a message;
- Barrier completion waiting time detected; Time needed to finish an MPI barrier
- Barrier waiting time detected;Waiting time in front of MPI barriers
- Latesender (wrong order from same source) waiting time detected; Wrong order situation due to messages received from the same source;
- Latesender (wrong order from different source) waiting time detected; Wrong order situation due to messages received from different sources
- Late Receiver waiting time detected; Time a sending process is waiting
- for the receiver to become ready
- N-to-N completion waiting time detected; Time needed to finish a n-to-n collective operation
- Wait before N-to-N detected; Time due to inherent synchronization in MPI n-to-n operations
- Late broadcast waiting time detected; Waiting time due to a late sender in MPI 1-to-n operations
- Earlyscan waiting time detected; Waiting time due to an early receiver in an MPI scan operation
- Early Reduce waiting time detected; Waiting time due to an early receiver in MPI n-to-1 operations
- MPI Init Exit; Time spent in MPI initialization calls

Solution rules

- Loop not unrolled optimally;unroll;my criteria;this field is reserved
- TlbMiss;large_page;using default criteria;large tlbmisses might be alleviated through large page usage
- *;compiler_msg;my criteria;get the compiler hints and messages

Solution scenarios

- Source code modification
- Compiler directives
- Polyhedral framework with compiler to generate better binary
- Environment variables
- Suggestions

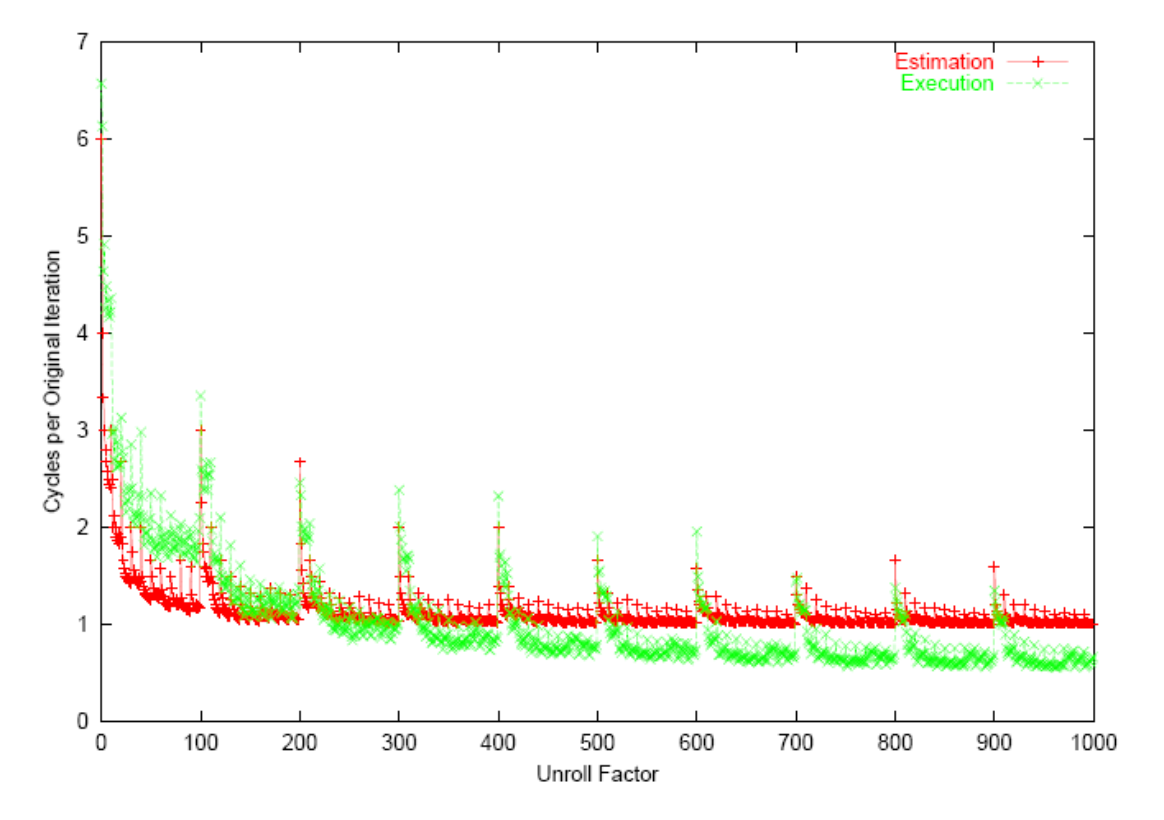
Cases:

- Finding the right unroll factor
- Performance tuning for LBMHD
- Communication/computation overlap

Unroll-and-jam

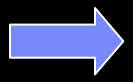
- Possibly the most frequently used optimizations
- Compiler oftentimes does not give the best factor
- Runtime metrics help pinpoint the loops to focus on
- Exhaustive search of the unroll space
  - Model-guided
  - Register allocation
  - Impact on prefetching
  - Generate “instructions” to “execute” on the machines
  - Select the best factor

Performance estimation



Source code modification

```
 ….
DO 50 J=1,NP1
   DO 50 I=1,MP1
   PSI(I,J) = A*SIN((I-.5D0)*DI)*SIN((J-
    .5D0)*DJ)
   P(I,J) = PCF*(COS(2.D0*(I-1)*DI)
  1             +COS(2.D0*(J-1)*DJ))+50000.D0
 50 CONTINUE
 ……
```



```
      do J = 1, 1 + (((((NP1)-1)/1)/2)-1)*1*2,  1*2
         do I = 1, 1 + (((((MP1)-1)/1)/2)-1)*1*2,  1*2
C           J[0] I[0]
         PSI (I ,J ) =A *SIN ( (I - .5D0 ) *DI ) *SIN ( (J - .5D0 ) *DJ
          )
         P (I ,J ) =PCF * (COS ( 2.D0 * (I - 1 ) *DI )
        1 +COS ( 2.D0 * (J - 1 ) *DJ ) ) + 50000.D0
         CONTINUE
C           J[0] I[1]
         PSI ((I+1) ,J ) =A *SIN ( ((I+1) - .5D0 ) *DI ) *SIN ( (J -
          .5D0
        1 ) *DJ )
         P ((I+1) ,J ) =PCF * (COS ( 2.D0 * ((I+1) - 1 ) *DI )
        1 +COS ( 2.D0 * (J - 1 ) *DJ ) ) + 50000.D0
         CONTINUE
C           J[1] I[0]
         PSI (I ,(J+1) ) =A *SIN ( (I - .5D0 ) *DI ) *SIN ( ((J+1) -
          .5D0
        1 ) *DJ )
         P (I ,(J+1) ) =PCF * (COS ( 2.D0 * (I - 1 ) *DI )
        1 +COS ( 2.D0 * ((J+1) - 1 ) *DJ ) ) + 50000.D0
         CONTINUE
C           J[1] I[1]
         PSI ((I+1) ,(J+1) ) =A *SIN ( ((I+1) - .5D0 ) *DI ) *SIN ( (
        1(J+1) - .5D0 ) *DJ )
         P ((I+1) ,(J+1) ) =PCF * (COS ( 2.D0 * ((I+1) - 1 ) *DI )
        1 +COS ( 2.D0 * ((J+1) - 1 ) *DJ ) ) + 50000.D0
         CONTINUE
         enddo
         do I = 1 + ((((MP1)-1)/1)/2) * 1 * 2,  (MP1),  1
C           J[0] I[0]
         PSI (I ,J ) =A *SIN ( (I - .5D0 ) *DI ) *SIN ( (J - .5D0 ) *DJ
          )
         P (I ,J ) =PCF * (COS ( 2.D0 * (I - 1 ) *DI )
        1 +COS ( 2.D0 * (J - 1 ) *DJ ) ) + 50000.D0
         CONTINUE
C           J[1] I[0]
         PSI (I ,(J+1) ) =A *SIN ( (I - .5D0 ) *DI ) *SIN ( ((J+1) -
          .5D0
        1 ) *DJ )
         P (I ,(J+1) ) =PCF * (COS ( 2.D0 * (I - 1 ) *DI )
        1 +COS ( 2.D0 * ((J+1) - 1 ) *DJ ) ) + 50000.D0
         CONTINUE
         enddo
         enddo
         do J = 1 + ((((NP1)-1)/1)/2) * 1 * 2,  (NP1),  1
         do I = 1, 1 + (((((MP1)-1)/1)/2)-1)*1*2,  1*2
```

LBMHD

- Plasma Physics

  Lattice Boltzmann approach for magneto-hydrodynamics
- Hot spot analysis results: Two functions consume 99.0% of time.
  - COLLISION: 59.602 sec (67.0%)
  - STREAM: 28.366 sec (32.0%)
  - Others: 0.896 sec (1.0%)
- Optimization steps

  STEP1: LARGEPAGES (16 M page)
  - Allocate data variables (f, feq, g, geq) on the data section (Originally allocated on the BSS section).

  STEP2: TRANSPOSE_A or TRANSPOSE_B (for COLLISION optimization)
  - Transpose index order of data variables (e.g. from g(i, j, k, l) to g(l, k, i, j)).
  - Interleave (f and feq) and (g and geq) into two arrays using "Type" (Originally four independent variables) (TRANSPOSE_B only)

  STEP3: LOOPINTERCHANGE (for STREAM optimization)
  - Change loop order of the STREAM function to mitigate effects of TRANSPOSE_A and TRANSPOSE_B.

Description of STEP2 TRANSPOSE_A or _B (for COLLISION optimization)

- Observations from the source code
  - Memory access pattern is not stride-1.

```
do j = jsta, jend
  do i = ista, iend
    …
    do k = 1, 4
      Bt2 = Bt2 + g(i, j, k, 1) * g(i, j, k+4, 2) …
      …
    enddo
    …
    do k = 1, 8
      geq(i,j,k,1) = Bfac * g(i,j,k,1)+ …
      …
    enddo
  enddo
enddo
```

Loop nesting order: k, i, j

NOT MATCH

Subscripts order: i, j, k

  - Loop nesting order cannot be changed because of dependency.

```
do k = 1, 4
  vt1 = vt1 + c(k,1)*f(i,j,k) + …
  …
enddo
```

"k" should be innermost to calculate the total (vt1)

  - Two pairs of arrays (f/feq and g/geq) are accessed with the same pattern.
- Optimization (Either TRANSPOSE_A or TRANSPOSE_B to be applied)
  - TRANSPOSE_A: Make memory access pattern stride-1 access by transposing dimension orders as follows;

```
Declaration Part REAL,DIMENSION (-1:DX+2,-1:DY+2,9,2):: g,geq
Reference Part   g(i,j,k,l), geq(i,j,k,l)
➔
Declaration Part REAL,DIMENSION (2,9,-1:DX+2,-1:DY+2):: g,geq
Reference Part   g(l,k,i,j), geq(l,k,i,j)
```

  - TRANSPOSE_B: TRANSPOSE_A and interleave two arrays (f/feq and g/geq) into one array using Fortran90' s Type as follows;

```
Declaration Part REAL,DIMENSION (-1:DX+2,-1:DY+2,9,2):: g,geq
Reference Part   g(l,k,i,j), geq(l,k,i,j)
➔
Declaration Part Type (real g, real geq) realg
Declaration Part Realg ggeq(2,9,-1,2050,-1,2050)
Reference Part   ggeq(l,k,i,j)%g, ggeq(l,k,i,j)%geq
```

SUBROUTINE COLLISION

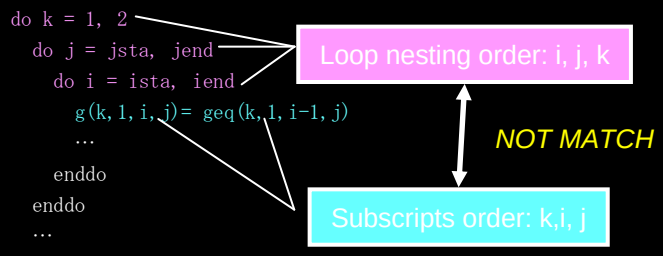
```
SUBROUTINE COLLISION
  USE mhd_vars
  IMPLICIT NONE
  real vt1, vt2, Bt1, Bt2, trho, rhoinv
  real vdotck(8), bdotck(8)
  do j = jsta, jend
    do i = ista, iend
      vt1 = 0    !tempv1 = 0
      vt2 = 0    !tempv2 = 0
      Bt1 = 0    !tempB1 = 0
      Bt2 = 0    !tempB2 = 0
      trho = rho(i,j)
      rhoinv = 1/trho

      do k = 1, 4
        vt1 = vt1 + c(k,1)*f(i,j,k) + c(k+4,1)*f(i,j,k+4)
        vt2 = vt2 + c(k,2)*f(i,j,k) + c(k+4,2)*f(i,j,k+4)
        Bt1 = Bt1 + g(i,j,k,1) + g(i,j,k+4,1)
        Bt2 = Bt2 + g(i,j,k,2) + g(i,j,k+4,2)
      enddo

      vt1 = vt1*rhoinv
      vt2 = vt2*rhoinv
      Bt1 = Bt1 + geq(i,j,9,1)
      Bt2 = Bt2 + geq(i,j,9,2)

      v2 = vt1**2 + vt2**2
      B2 = Bt1**2 + Bt2**2
      ! Used below in odd feq
      temp1= .25*trho*cs2+ .125*(-trho*v2 + 3.0*B2)

      do k = 1, 8
        vdotc = c(k,1)*vt1 + c(k,2)*vt2
        Bdotc = c(k,1)*Bt1 + c(k,2)*Bt2
        feq(i,j,k) = vfac*f(i,j,k)+vtauinv*(temp1+trho*.25*vdotc+ &
             .5*(trho*vdotc**2- Bdotc**2))
        geq(i,j,k,1) = Bfac*g(i,j,k,1)+ Btauinv*.125*(theta*Bt1+ &
             2.0*Bt1*vdotc- 2.0*vt1*Bdotc)
        geq(i,j,k,2) = Bfac*g(i,j,k,2)+ Btauinv*.125*(theta*Bt2+ &
             2.0*Bt2*vdotc- 2.0*vt2*Bdotc)
      enddo

      v(i,j,1) = vt1
      v(i,j,2) = vt2
      B(i,j,1) = Bt1
      B(i,j,2) = Bt2
      feq(i,j,9) = vfac*feq(i,j,9)+
                   vtauinv*((1.0-2.0*cs2)*trho-trho*v2-B2)
      geq(i,j,9,1) = Bfac*geq(i,j,9,1)+Btauinv*(1.0-theta)*B(i,j,1)
      geq(i,j,9,2) = Bfac*geq(i,j,9,2)+Btauinv*(1.0-theta)*B(i,j,2)
    enddo
  enddo
END SUBROUTINE COLLISION
```

10 memory load and 8 arithmetic instructions

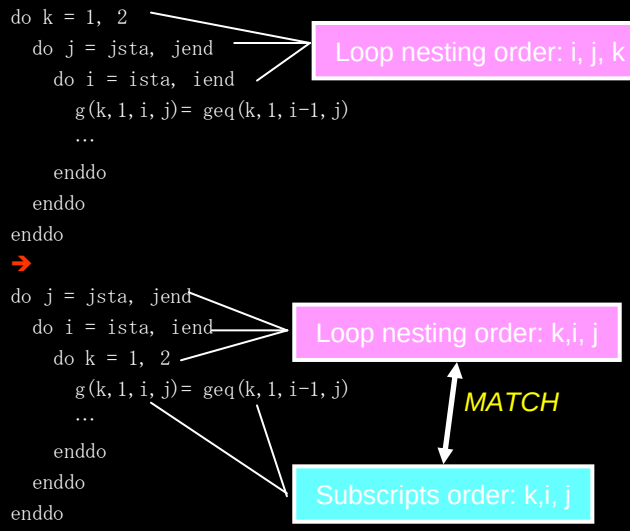
8 memory load/store and 18 arithmetic instructions

Description of STEP3: LOOPINTERCHANGE (for STREAM optimization)

- Observations from the source code
  - Assuming TRANSPOSE_A or B applied, memory access pattern is not stride-1.



  - All loops are perfectly nested, and have no loop carried dependency.
- Optimization
  - LOOPINTERCHANGE: Change the loop nesting order to fit with the new dimension order modified by TRANSPOSE_A (or B)



SUBROUTINE STREAM (After TRANSPOSE_A applied)

```
SUBROUTINE STREAM
  USE mhd_vars
  IMPLICIT NONE
  include 'mpif.h'
  INTEGER istatus(MPI_STATUS_SIZE)
  INTEGER jmone,jpone,jmtwo,jptwo,imone,ipone,imtwo,iptwo
  real tempv1, tempv2, tempB1, tempB2, temprho, rhoinv
  real vdotck(8), bdotck(8)

  CALL NEIGHBOURS  ! Get ghost cells from neighbouring PEs
  do j = jsta, jend
    do i = ista, iend
      f(1,i,j)= feq(1,i-1,j)
      f(3,i,j)= feq(3,i,j-1)
      f(5,i,j)= feq(5,i+1,j)
      f(7,i,j)= feq(7,i,j+1)
    enddo
  enddo

  do j = jsta, jend
    do i = ista, iend
      f(2,i,j)= w1*feq(2,i,j)+ w2*feq(2,i-1,j-1)+ w3*feq(2,i-2,j-2)
      f(4,i,j)= w1*feq(4,i,j)+ w2*feq(4,i+1,j-1)+ w3*feq(4,i+1,j-2)
      f(6,i,j)= w1*feq(6,i,j)+ w2*feq(6,i+1,j+1)+ w3*feq(6,i+2,j+2)
      f(8,i,j)= w1*feq(8,i,j)+ w2*feq(8,i-1,j+1)+ w3*feq(8,i-2,j+2)
    enddo
  enddo

  do k = 1, 2
    do j = jsta, jend
      do i = ista, iend
        g(k,1,i,j)= geq(k,1,i-1,j)
        g(k,3,i,j)= geq(k,3,i,j-1)
        g(k,5,i,j)= geq(k,5,i+1,j)
        g(k,7,i,j)= geq(k,7,i,j+1)
      enddo
    enddo

    do j = jsta, jend
      do i = ista, iend
        g(k,2,i,j)= w1*geq(k,2,i,j)+ w2*geq(k,2,i-1,j-1)+
                    w3*geq(k,2,i-2,j-2)
        g(k,4,i,j)= w1*geq(k,4,i,j)+ w2*geq(k,4,i+1,j-1)+
                    w3*geq(k,4,i+1,j-2)
        g(k,6,i,j)= w1*geq(k,6,i,j)+ w2*geq(k,6,i+1,j+1)+
                    w3*geq(k,6,i+2,j+2)
        g(k,8,i,j)= w1*geq(k,8,i,j)+ w2*geq(k,8,i-1,j+1)+
                    w3*geq(k,8,i-2,j+2)
      enddo
    enddo
  enddo
END SUBROUTINE STREAM
```

8 memory load/store and 0 arithmetic instructions

16 memory load/store and 12 arithmetic instructions

Bottleneck detection

$$PM\_CMPLU\_STALL\_LSU/PM\_CYC > \alpha \;\&\&$$
$$SA\_STRIDE\_ONE\_ACCESS\_RATE \leq \beta \;\&\&$$
$$SA\_REGULAR\_ACCESS\_RATE(n) > SA\_STRIDE\_ONE\_ACCESS\_RATE + \gamma$$

Using directives as solutions

```
REAL, DIMENSION(-1:DX+2,-1:DY+2,9), TARGET   :: f, feq
REAL, DIMENSION(-1:DX+2,-1:DY+2,9,2), TARGET :: g, geq
Subroutine stream
….
do k = 1, 2
do j = jsta, jend
do i = ista, iend
  g(i,j,1,k)= geq(i-1,j,1,k)
  g(i,j,3,k)= geq(i,j-1,3,k)
  g(i,j,5,k)= geq(i+1,j,5,k)
  g(i,j,7,k)= geq(i,j+1,7,k)
enddo
Enddo
….
Subroutine collision
…
do i = ista, iend
do j = jsta, jend
do k = 1, 8
feq(i,j,k)=vfac*f(i,j,k)+vtauinv*(temp1+trho*.25*vdotc+ &
          .5*(trho*vdotc**2- Bdotc**2))
 geq(i,j,k,1)= Bfac*g(i,j,k,1)+ Btauinv*.125*(theta*Bt1+ &
              2.0*Bt1*vdotc- 2.0*vt1*Bdotc)
 geq(i,j,k,2)= Bfac*g(i,j,k,2)+ Btauinv*.125*(theta*Bt2+ &
              2.0*Bt2*vdotc- 2.0*vt2*Bdotc)
enddo
```

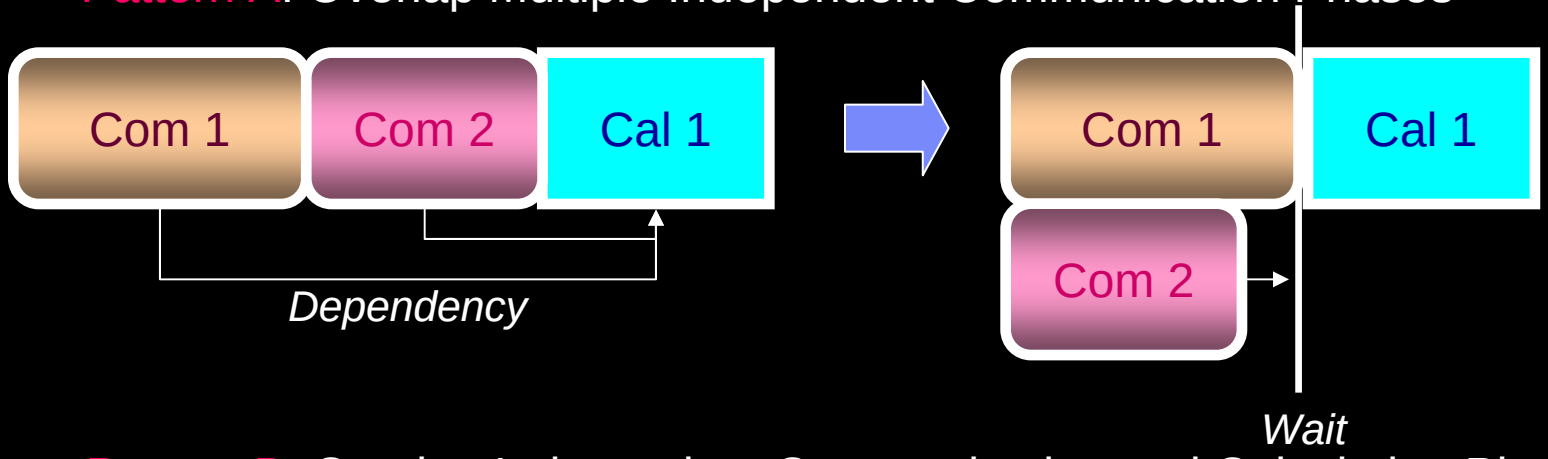
```
!IBM* SUBSCRIPTORDER(f(3,1,2),feq(3,1,2),g(4,3,1,2),geq(4,3,1,2))

Subroutine stream
….
do j = jsta, jend
do i = ista, iend
do k = 1, 2
g(i,j,1,k)= geq(i-1,j,1,k)
  g(i,j,3,k)= geq(i,j-1,3,k)
  g(i,j,5,k)= geq(i+1,j,5,k)
  g(i,j,7,k)= geq(i,j+1,7,k)
enddo
Enddo
….
Subroutine collision
…
do i = ista, iend
do j = jsta, jend
do k = 1, 8
feq(i,j,k)=vfac*f(i,j,k)+vtauinv*(temp1+trho*.25*vdotc+ &
          .5*(trho*vdotc**2- Bdotc**2))
 geq(i,j,k,1)= Bfac*g(i,j,k,1)+ Btauinv*.125*(theta*Bt1+ &
              2.0*Bt1*vdotc- 2.0*vt1*Bdotc)
 geq(i,j,k,2)= Bfac*g(i,j,k,2)+ Btauinv*.125*(theta*Bt2+ &
              2.0*Bt2*vdotc- 2.0*vt2*Bdotc)
enddo
```

Communication/Computation Overlapping

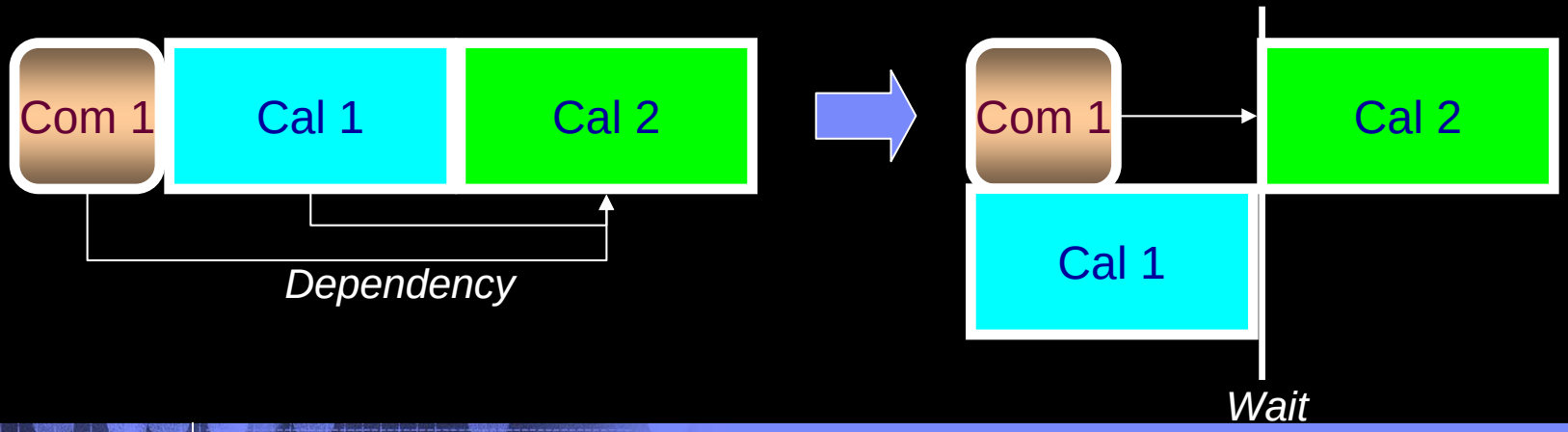
Two Optimization Patterns by Overlapping Communication

Policy: Optimize Behavior in each MPI Process without Changing its Communication Behavior

- Pattern A: Overlap Multiple Independent Communication Phases



- Pattern B: Overlap Independent Communication and Calculation Phases



Sample Program including Two Overlap Patterns

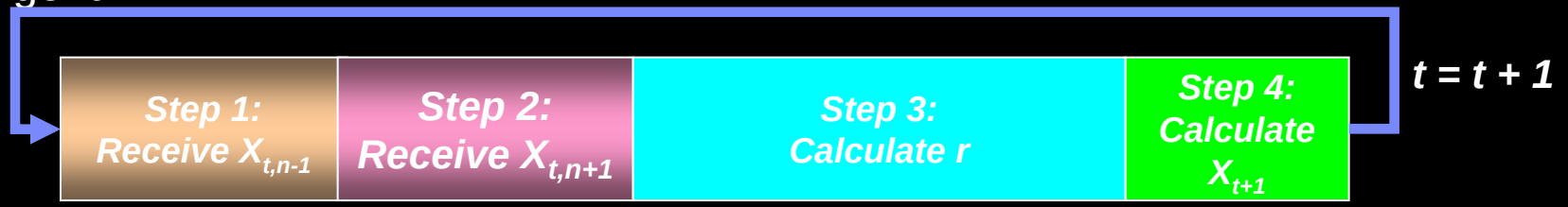
- Function

  Calculate $X_{t,n}(k)$ = "value of k-th data in node n at step t, " for each node n and step t

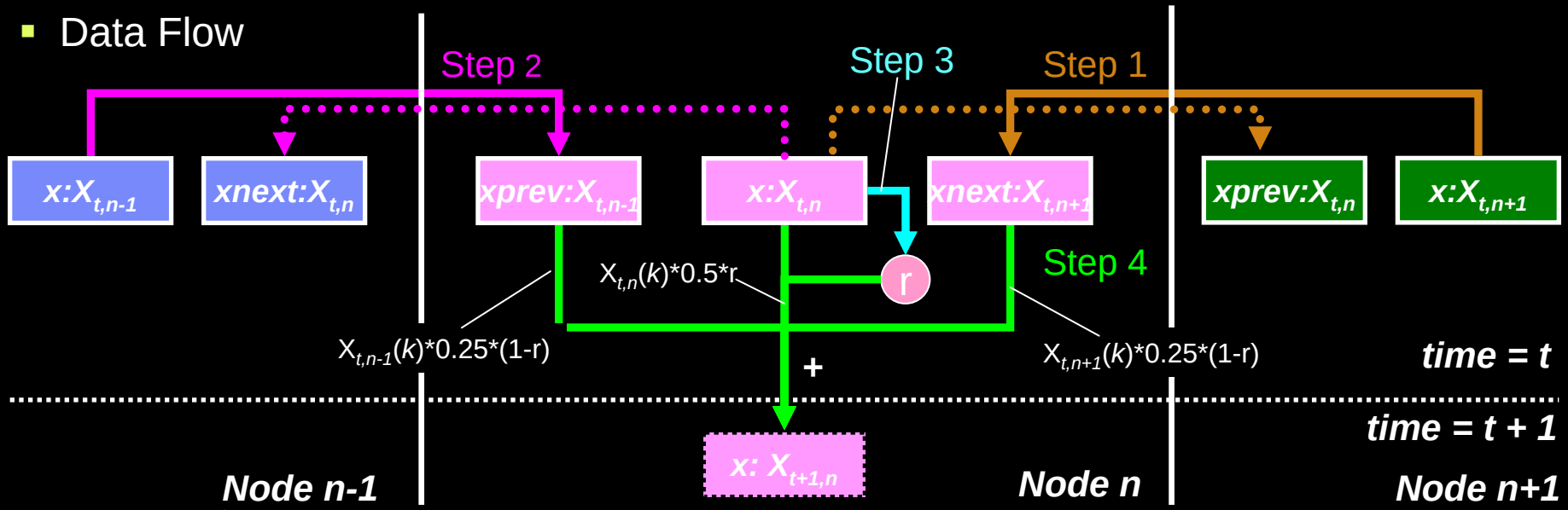
  $s = \sum_{k=1}^{n} X_{t,n}(k) * \sin(X_{t,n}(k) * o)$, and $r = s / (1 + s)$

  $X_{t+1,n}(k) = X_{t,n}(k) * 0.5 * r + (X_{t,n-1}(k) + X_{t,n+1}(k)) * 0.25 * (1 - r)$

- Algorithm



- Data Flow

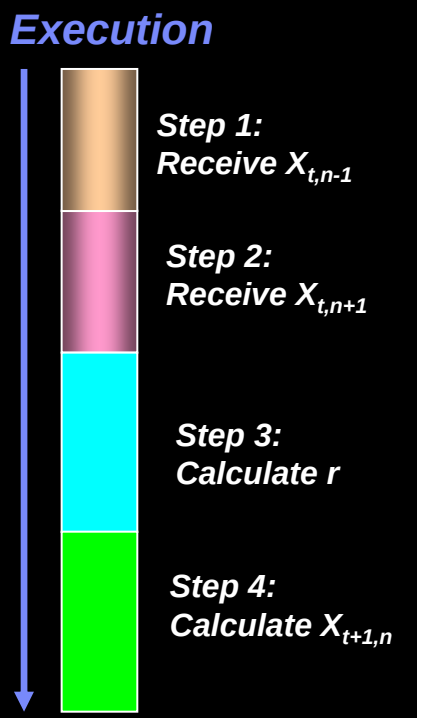


Original Source Code

```
do t = 1, m
  call MPI_SENDRECV(x, n, MPI_DOUBLE_PRECISION, next, 0,
-                   xprev, n, MPI_DOUBLE_PRECISION, prev,
-                   0, MPI_COMM_WORLD, status, ierr)
  if (ierr .ne. 0) stop 'ERROR IN MPI_SENDRECV (next/prev)'
  call MPI_SENDRECV(x, n, MPI_DOUBLE_PRECISION, prev, 0,
-                   xnext, n, MPI_DOUBLE_PRECISION, next,
-                    0, MPI_COMM_WORLD, status, ierr)
  if (ierr .ne. 0) stop 'ERROR IN MPI_SENDRECV (prev/next)'
  s = 0.0
  do i = 1, n
    s = s + x(i) * sin(x(i) * pi)
  enddo
  r = s / (1 + s)
  do i = 1, n
    x(i) = x(i) * 0.5 * r +
-          (xprev(i) + xnext(i)) * 0.25 * (1 - r)
    check = check + x(i)
  enddo
enddo
```

MPI_SENDRECV

MPI_SENDRECV



Source Code of Optimization 1

```
do t = 1, m
-   call MPI_IRECV(xprev, n, MPI_DOUBLE_PRECISION, prev,
                   0, MPI_COMM_WORLD, rreq1, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_IRECV (prev)'
-   call MPI_IRECV(xnext, n, MPI_DOUBLE_PRECISION, next,
                   0, MPI_COMM_WORLD, rreq2, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_IRECV (next)'
-   call MPI_ISEND(x, n, MPI_DOUBLE_PRECISION, next, 0,
                   MPI_COMM_WORLD, sreq1, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_ISEND (next)'
-   call MPI_ISEND(x, n, MPI_DOUBLE_PRECISION, prev, 0,
                   MPI_COMM_WORLD, sreq2, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_ISEND (prev)'
    call MPI_BARRIER(MPI_COMM_WORLD, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_MPI_BARRIER'
    call MPI_WAIT(sreq1, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (SEND prev)'
    call MPI_WAIT(sreq2, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (SEND next)'
    call MPI_WAIT(rreq1, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (RECV prev)'
    call MPI_WAIT(rreq2, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (RECV next)'
    s = 0.0
    do i = 1, n
      s = s + x(i) * sin(x(i) * pi)
    enddo
    r = s / (1 + s)
    do i = 1, n
      x(i) = x(i) * 0.5 * r +
-            (xprev(i) + xnext(i)) * 0.25 * (1 - r)
      check = check + x(i)
    enddo
enddo
```

MPI_IRECV

MPI_IRECV

MPI_ISEND

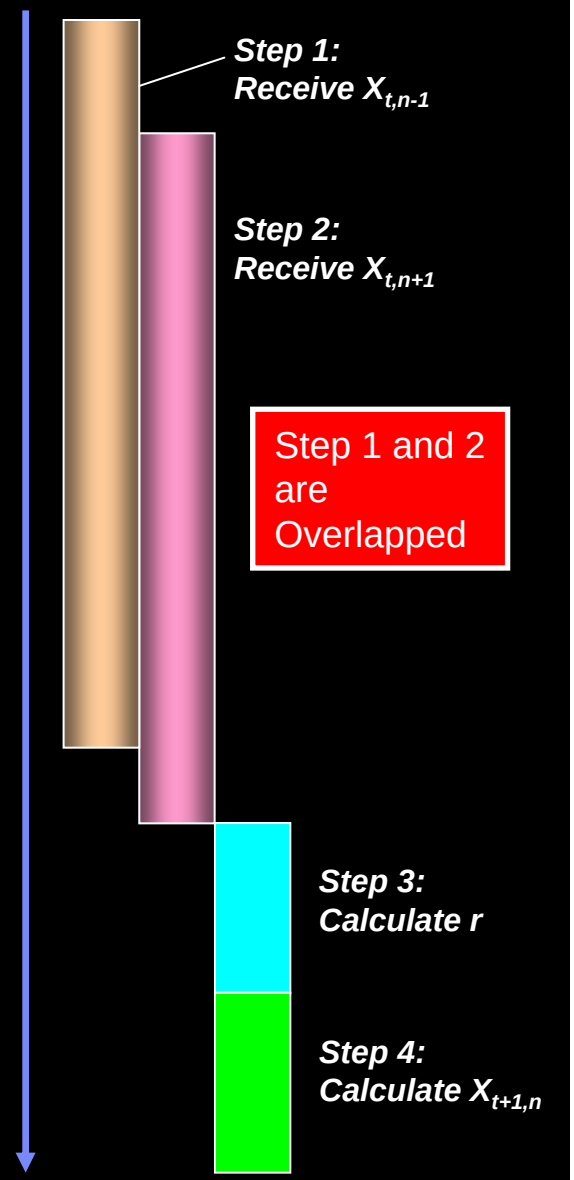
MPI_ISEND

MPI_WAIT

MPI_WAIT

MPI_WAIT

MPI_WAIT



Source Code of Optimization 2

```
do t = 1, m
-   call MPI_IRECV(xprev, n, MPI_DOUBLE_PRECISION, prev,
                   0, MPI_COMM_WORLD, rreq1, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_IRECV (prev)'
-   call MPI_IRECV(xnext, n, MPI_DOUBLE_PRECISION, next,
                   0, MPI_COMM_WORLD, rreq2, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_IRECV (next)'
-   call MPI_ISEND(x, n, MPI_DOUBLE_PRECISION, next, 0,
                   MPI_COMM_WORLD, sreq1, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_ISEND (next)'
-   call MPI_ISEND(x, n, MPI_DOUBLE_PRECISION, prev, 0,
                   MPI_COMM_WORLD, sreq2, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_ISEND (prev)'
    call MPI_BARRIER(MPI_COMM_WORLD, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_MPI_BARRIER '
    s = 0.0
    do i = 1, n
      s = s + x(i) * sin(x(i) * pi)
    enddo
    r = s / (1 + s)
    call MPI_WAIT(sreq1, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (SEND prev)'
    call MPI_WAIT(sreq2, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (SEND next)'
    call MPI_WAIT(rreq1, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (RECV prev)'
    call MPI_WAIT(rreq2, status, ierr)
    if (ierr .ne. 0) stop 'ERROR IN MPI_WAIT (RECV next)'
    do i = 1, n
      x(i) = x(i) * 0.5 * r +
-            (xprev(i) + xnext(i)) * 0.25 * (1 - r)
      check = check + x(i)
    enddo
enddo
```

MPI_IRECV

MPI_IRECV

MPI_ISEND

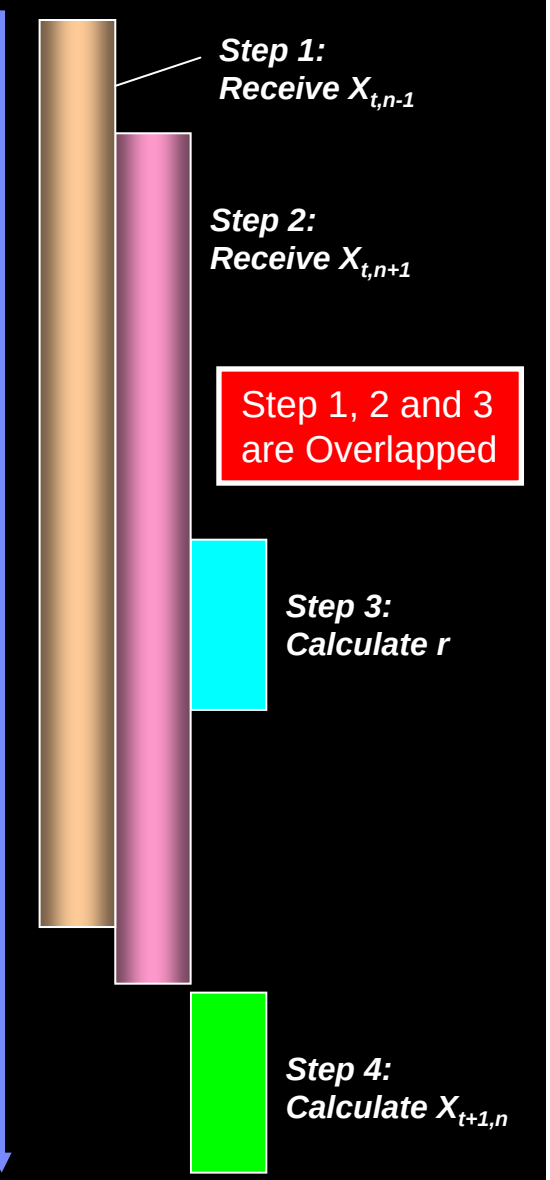
MPI_ISEND

MPI_WAIT

MPI_WAIT

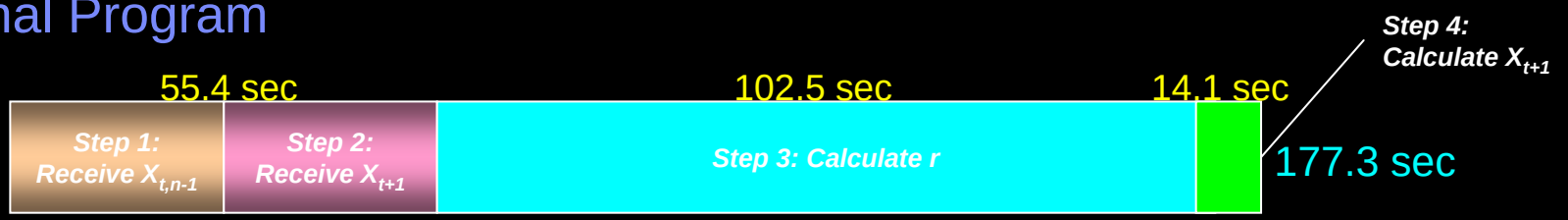
MPI_WAIT

MPI_WAIT

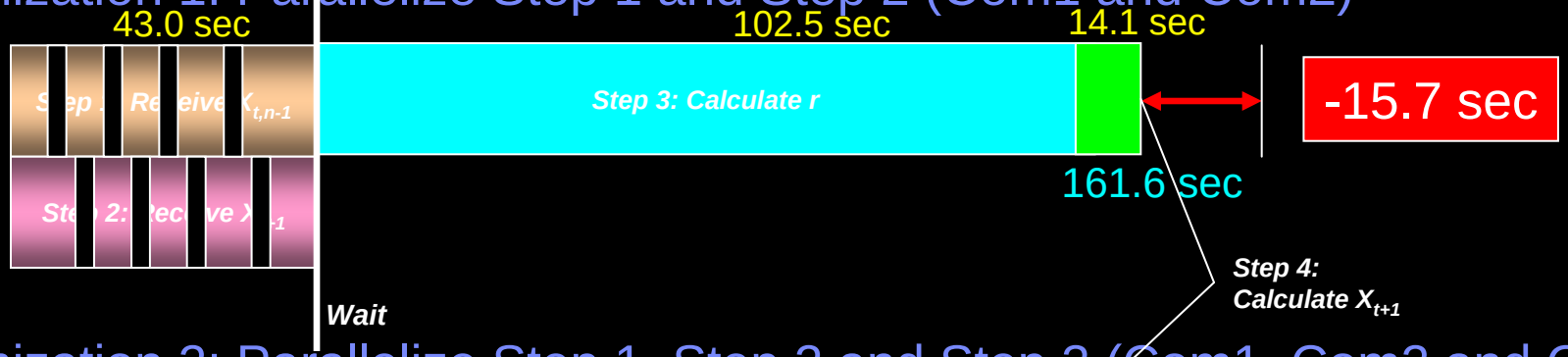


Performance Results (Blue Gene/P 32 node, SMP mode, 1 proc/node)

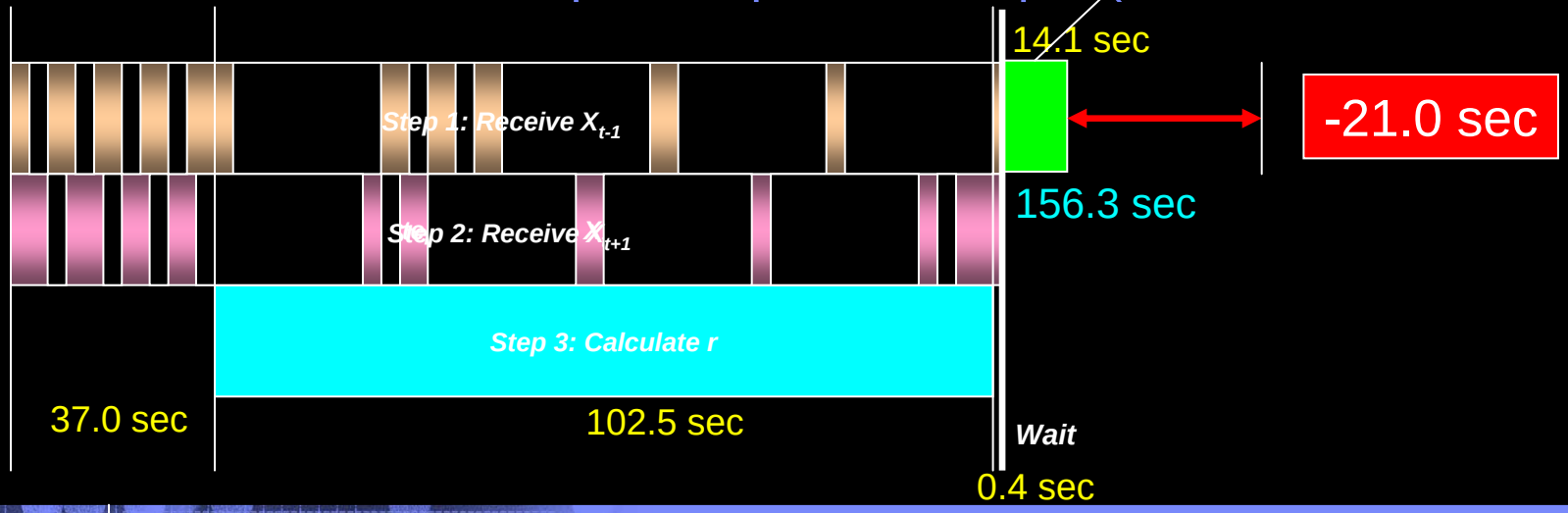
- Original Program



- Optimization 1: Parallelize Step 1 and Step 2 (Com1 and Com2)



- Optimization 2: Parallelize Step 1, Step 2 and Step 3 (Com1, Com2 and Cal1)



Solution Implementation

```
Forward AFTER LINE 48:ST_ASSIGNMENT 2 [
  0:VAR(r),
  1:OP("/" 2[VAR(s),OP("+" 2[CONST(INT#1),VAR(s)])]),
]


Wait: InsertAfter [48:9:48:74] [
        call MPI_WAIT(NEW0_1, status, ierr)
        call MPI_WAIT(NEW0_2, status, ierr)
]
--------
Backward BEFORE LINE 36:ST_CALL 14 [
]
Forward AFTER LINE 48:ST_ASSIGNMENT 2 [
  0:VAR(r),
  1:OP("/" 2[VAR(s),OP("+" 2[CONST(INT#1),VAR(s)])]),
]

Wait: InsertAfter [48:9:48:74] [
        call MPI_WAIT(NEW1_1, status, ierr)
        call MPI_WAIT(NEW1_2, status, ierr)
]
```

Polyhedral for loop tiling

- No source code change
- After bottleneck analysis, in solution determination, hpcst automatically generates a script file that is fed back to the compiler
- Script provides command for optimization for the compiler to apply on the intermediate representation (W-code)
- Potential of composing transformations
- Can be used to implement many standard transformations

```
# Compute dependences syntax:
# PT_depcompute(bool RAR, bool ADA, bool summaryAll, bool summaryRAW)
#

PT_depcompute(1,1,0,0)

dumpprog erhs_initial

# Tile the i and j loops only
#PT_tile({0,0},1,2,55,55)
#dumpcode lud_afterTiling

# Fuse loops together
#PT_fusion ({0,0} ,{1,0});
#dumpcode main_afterFusion
```

Support for UPC

- Bottlenecks for UPC applications based on UPC profiling and tracing library
  - Load balancing issues
- Suggestions for removing bottlenecks
  - Communication aggregation