FCJL8&5fJs9p=q

Hs6Q<A4D6-8~$1JENs2=%3%s%Q%$%i

hetero-TINPAR $N

F0E*Ii2YJ,;6J}<0$N2~NI

;XF3654 1 IYEDbC<#65<x

5~ETBg3X9)3XIt>pJs9)3X2J

EDCf?5;J

J?@.10G/2 7n13F|

Hs6Q<A4D6-8~$1JBNs2=%3%s%Q%$%i*hetero-TINPAR* $N F0E*Ii2YJ,;6J}<0$N2~NI

EDCf?5;J FhMF9<35

=hM}G=NO$N0[$J$k7W;;5!$,@\B3$5$l$F$$$kHs6Q<A4D6-GO3F7W;;5!$N7W;;G=NO$r:GBg8B$K0z$-=P9K$O!"7W;;5!$NG=NO$K1~$8$?%?%9%/J,;6$,I,MWHJ$k!#$^$?!"%^%k%A%f!<%6!<4D6-$G$O!"B>$N%f!<%6!<%W%m%;%9JIKhCFIi2Y$,F0E*$KJQ2=9k$?$a!"3NJQ2=$KBP1~$7$F7W;;5!;q8;$rM-8z$K;H$&$?$a$KF0E*Ii2YJ,;65!G=$bI,MWH5lk!#2f!9O3Nh$&$J4D6-$KBP1~$9k?$a!"3F7W;;5!$N7W;;G=NO$K1~$8$F%?%9%/$rG[J,9kHs6Q<A4D6-8~$1JBNs2=%3%s%Q%$%i*hetero-TINPAR* $r3+H/$7$F$$k!#K\Js9p=qGO!"*hetero-TINPAR* $NF0E*Ii2YJ,;65!G=$N2~NIKD$$F=RYk!#

hetero-TINPAR GO!"Cj>]%W%m%;%C%5$H$$&35G0$rMQ$$F!"Hs6Q<A4D6-$KBP1~$7$F$$k!#Cj>]%W%m%;%C%5HO!"F1Ey$N=hM}G=NO$r;}C?2>A[E*$J%W%m%;%C%5$N3HG"$k!#*hetero-TINPAR* GO!"Cj>]%W%m%;%C%5$K6QEy$K%?%9%/$rJ,;6$5$;!"$3$NCj>]%W%m%;%C%5$rJ#?t8D!"<B%W%m%;%C%5$K3d$jEvFk3HKh$j!"Hs6Q<A4D6-$KBP1~7?Ii2YJ,;6$r<B8=$7$F$$k!#

hetero-TINPAR $NF0E*Ii2YJ,;65!G=$O!"UQF0$9$kIi2Y$K1~$8$F!"Cj>]%W%m%;%C%5$NG[J,Hf$rJQ99$7!"$=$lK7$?$,CFCj>]%W%m%;%C%5$r<B%W%m%;%C%54V$GE>Aw9k3HKhCF<B8=5l$F$$k!#

=>Mh$NF0E*Ii2YJ,;65!G=$G$O!#Hf3SE*C1=c$J5!9=KhCF<B8=5l$F$$F$$$k$?$a!"MM!9$J7W;;5!4D6-!"MM!9$J%"%W%j%1!<%7%g%sKBP7$F!">o$K:GE,$JIi2YJ,;6$,<B8=5l$F$$kHO8@$$$,$?$$!#LdBjE@H7FO!"0J2<Nh$&$JbN$,$"2ilk!#Bh1 $K!"Cj>]%W%m%;%C%5$N3dEvJ}<0$K!"C1=c$JO"B33dEvN_$,2DG=$G$"$k!#3N$?$a!"<B%W%m%;%C%5$NHV9f$H<B:]$N7W;;5!$NBP1~Kh$kF0E*Ii2YJ,;6$KMW9k;~4VXN1F6A$,Bg$-$$!#Bh2 $K!"A4$F$N<B%W%m%;%C%5$KCj>]%W%m%;%C%5$r>/$J$/$H$b1 DOG[J,7J1lPJiJ$$!#3N$?$a!"Hs>o$K=hM}G=NO$NDc$$<B%W%m%;%C%5$,B8:_$7$?>19g!"$=$N<B%W%m%;%C%5$KG[J,5l$?Cj>]%W%m%;%C%51 $DJ,$N=hM}N?aK!"A4BN$N<B9T;~4V$,A}Bg9k!#Bh3 $K!":FJ,;6$N$?$a$NIi2Y>pJs<}=8$N$?$a$K!"<B:]$K$O:FJ,;6$r9ToJ$/$F$b!"Bg$-$J

%*!<%P!<%X%C%I$rH<$&A4<B%W%m%;%C%5$NF14|$,I,MWHJ$k!#

K\<jK!GO!"3Nh&$JLdBj$rJz$($k=>Mh$N*hetero-TINPAR*$NF0E*Ii2YJ,;65!G=KBP7$F!"0J2<$N2~NI$r2C$(k3HKhC$F!"$h$jB?$/$N%"%W%j%1!<%7%g%s$H!"F0E*$KJQ2=$9$k7W;;5!4D6-$KBP7Fhj9bB.<B9TG-kh$&$K7?!#Bh1$K!"Cj>]%W%m%;%C%5$N3dEvJ}K!$,=>Mh$NC1=c$J!"O"B3E*$K3djEvFkH$$&J}K!$K2C$(E>Aw9kCj>]%W%m%;%C%5?t$r:G>.8B$KM^$(!"F0E*Ii2YJ,;6;~$N%3%9%H$r:G>.$K9kJ}K!$rA*Br$G$-$kh&K7$?!#$^$?!"$3$N2$D$NCj>]%W%m%;%C%5$N3djEvFJ}$r!"<B9T$9$k%"%W%j%1!<%7%g%s$K$"<+F0E*$KA*Br5lkh$&$K7?!#Bh2$K!"=>Mh$O3F<B%W%m%;%C%5$KCj>]%W%m%;%C%5$r>/J/Hb1DOG[J,9kI,MW$,$"C?$,!"$3$N@)8B$rJ/$7!"Cj>]%W%m%;%C%5$NN3EYKHfY!"7W;;5!4V$G6KC<$J=hM}G=NO:9$,H/@8$7$?>19g!"9bIi2Y$KJC$F$$k<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,7J$$h$&$KbG$-$kh&K7$?!#Bh3$K!"=>Mh$O!"F0E*Ii2YJ,;65!G=$,MW5a7?Cj>]%W%m%;%C%5$NJQ2=NI$rH>8:5;$F$$?$,!"C1=c$KJQ2=NI$,%f!<%6!<$,;XDj7?ogCM0J2<$N>19g$OJQ2=5;$J$$$3HK9kJ}K!$bA*Br$G$-$kh&K7$?!#Bh4$K!"<+N'Ii2YH=CGJ}<0Kh$j!"3F%W%m%;%C%5$N<+J,$NIi2Y>pJs$N$_$rMQ$$$F!"Ii2YJQF0$,G'<1$G$-$kh&KJ$j!"B?Bg$J%*!<%P!<%X%C%I$rH<$&F14|rI,MWH7?!"F0E*Ii2YJ,;6$NI,MW@-$NH=CG$N%3%9%H$rBgI}$K:o8:$7$?!#$3lKhj!"IQHK$KF0E*Ii2YJ,;6$NI,MW@-$rH=CG$9k3H,G-kh$&$KJj!"3F7W;;5!$NIi2Y$,JQ2=7?>19g!"3NJQ2=$KIR46$KH?1~$7!"F0E*Ii2YJ,;6$r<B9T9k3HKh$j!"9bB.<B9T$r2DG=H7$?!#

SOR $HRed-Black SOR $N%W%m%0%i%`$rMQ$$$?@-G=I>2A$N7k2L!"K\<jK!$KhC$F!"Cj>]%W%m%;%C%5$N3dEvJ}<0$N2~NI$Khj!"=>Mh$N*hetero-TINPAR*$KHfYF!"10%$N@-G=8~>e$,<(5l$?!#<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,$7$J$$$3HKhC$F!"Cj>]%W%m%;%C%5$NN3EYHHfY!"7W;;5!4V$K6KC<$J=hM}G=NO:9$,$"$k>19g!"15%DxEY$N@-G=8~>e$,<($5l?!#$^$?!"F0E*$JIi2YJQF0$KBP$7!"<+N'Ii2YH=CGJ}<0$KhjIi2YJQF0$r8!=P$9k3HKhj!"F0E*$KIi2Y$,JQF0$7$?>19g!"JQF0$7$?3F7W;;5!$N=hM}G=NOHf$K!"Cj>]%W%m%;%C%5$NG[J,Hf$rB.d+$K9g$o$;$k3H$,$G$-$kh&KJC?!#3lKh$j!"*hetero-TINPAR*$Khj%3%s%Q%$k5$l$?%W%m%;%95Z$S!"Ii2YJQF0$N860x$HJC$?%W%m%;%9$,6&$K10%DxEY$N<B9T;~4V$NC;=L$,<(5l$?!#

hetero-TINPAR: a Parallelizing Compiler for Heterogeneous Computing Environment — Improvement of Dynamic Load Balancing Scheme —

Shinji TANAKA

Abstract

In heterogeneous computing environment which consists of processors with different computing power, tasks must be distributed in proportion to computing power of the processors to exploit their available computing power. In multi-user environment, a scheme is required that balances the loads of the parallel tasks adapting the change of loads brought about other tasks. We have been developing *hetero-TINPAR*, a parallelizing compiler for such heterogeneous computing environment. This report presents several improvements on the dynamic load balancing scheme of *hetero-TINPAR*.

To cope with heterogeneous computing environment, we have introduced a concept of *Abstract Processor*. An abstract processor represents one of virtual homogeneous parallel processors which have the same available computing power. Data elements of arrays are once distributed onto homogeneous abstract processors. Then several abstract processors are assigned to a real processor in proportion to the available computing power of the real processor.

In our dynamic load balancing scheme of *hetero-TINPAR*, the ratio of abstract processors assigned to real processors varies in proportion to the available computing power of the real processors and the abstract processors are exchanged among the real processors each others.

Because the strategy of the conventional dynamic load balancing scheme is simple, it is not possible to adapt the variety of applications and situations in dynamically changing environment. Firstly, because only contiguous abstract processors are allowed to be assigned to the same real processor, time spent to the dynamic load balancing depends on the fixed arrangement of real processors. Secondary, the overall performance may degraded by a real processor of low performance because at lease one abstract processor must be assigned to each real processor. Thirdly, all real processors must be synchronized and exchange their load information to determine whether to redistribute abstract processors,

even if the redistribution is not necessary. This synchronization brings large overhead.

This report therefore proposes the following improvements on the dynamic load balancing scheme of *hetero-TINPAR* to adapt the variety of applications and situations in dynamically changing environment.

Firstly, in addition to the current simple scheme of assigning abstract processors contiguously, we adopt another scheme which reduces the number of transfered abstract processors. One of these two strategies are selected depending on the applications at compile-time. Secondary, a dynamic load balancing scheme proposed can distribute no abstract processor to a real processor which has less available computing power than one which one abstract processor needs. Thirdly, the user is allowed to specify the threshold of the change of loads on each real processor to determine whether redistribution is performed. Fourthly, because all real processors must be synchronized when the conventional dynamic load balancing scheme checks the necessity of dynamic load balancing even if the dynamic load balancing is not required, this check amounts to much overhead. But the proposed scheme can determine the necessity of redistribution without synchronization. Then the cost of checking the necessity of dynamic load balancing is much reduced. Because the proposed scheme can check this necessity more frequently by honor to this improvement, it can react the change of the load of real processors sensitively.

As a result of the performance evaluation of the SOR and the Red-Black SOR applications, it is concluded that by the improvement the strategy of assigning abstract processors to real processors, the execution time is reduced by 10% at most. When there is much difference of computing power between real processors, by the improvement of assigning no abstract processors to the low-performance processor, the execution time is reduced by 15% at most. By checking the necessity of dynamic load balancing without synchronization, the change of the ratio of computing power of real processors reflects the ratio of distributing abstract processors quickly. Hence the execution times of both the process compiled by *hetero-TINPAR* and the process which causes the change of the load are reduced by 10%.

Hs6Q<A4D6-8~$1JBNs2=%3%s%Q%$%i*hetero-TINPAR* $N F0E*Ii2YJ,;6J}<0$N2~NI

L\<!

1 O8aK **1**

2 ***hetero-TINPAR*** $N35MW **2**

2.1 Cj>]%W%m%;%C%5 2

2.2 <B%W%m%;%C%5K*1kCj>]%W%m%;%C%5$N%(%_%e%l!<%7%g%s$NJ}K! 3

2.3 F0E*Ii2YJ,;65!G=. 4

2.4 =>Mh$NF0E*Ii2YJ,;65!G=$NLdBjE@ 6

3 F0E*Ii2YJ,;65!G=$N2~NI **7**

3.1 E,1~7?Cj>]%W%m%;%C%5$N3dEvJ}<0 7

3.1.1 O"B33dEvJ}<0$H:G>.0\F0%3%9%HJ}<0 7

3.1.2 NcBj%W%m%0%i%`$rMQ$$$?N>J}<0$NF0:n2r@b 8

3.1.3 :G>.0\F0%3%9%HJ}<0K*1kCj>]%W%m%;%C%5$N3dEvJ}?K 11

3.1.4 Cj>]%W%m%;%C%5$N3dEvJ}<0$N<+F0H=Dj 13

3.2 Ii2YG[J,$K4X$9$kogCM@)8f 13

3.2.1 Cj>]%W%m%;%C%5$N0\F0$N@)8B 13

3.2.2 Cj>]%W%m%;%C%5$rG[J,$5lJ$$<B%W%m%;%C%5 13

3.3 <+N'Ii2YH=CGJ}<0. 14

4 @-G=I>2A **18**

4.1 I>2A4D6- 18

4.1.1 I>2A%W%m%0%i%` 18

4.1.2 I>2A$K;HMQ$7$?7W;;5!4D6- 19

4.2 *hetero-TINPAR* KBP9$k2~NI$NI>2A 21

4.2.1 E,1~7?Cj>]%W%m%;%C%5$N3dEvJ}<0$NI>2A 21

4.2.2 Cj>]%W%m%;%C%5$rG[J,$5lJ$$<B%W%m%;%C%5$NI>2A . . . 23

4.2.3 <+N'Ii2YH=CGJ}<0$NI>2A 24

5 $*$ojK **26**

<U<- **27**

;29MJ88% **27**

IUO? **A-1**

A.1 $=$NB>$N%"%W%j%1!<%7%g%s$KhkI>2A7k2L A-1

1 O8aK

6aG/!"%o!<%/%9%F!<%7%g&s$d%Q!<%=%J%k%3%s%T%e!<%?$O!"0B2A$G9b@-G=$KJCF-F*$j!"$3li$N7W;;5!F1;N$O!"%$!<%5%M%C%H$JIKhC$FAj8_$K@\B3$5$l$F$$k!#B?$/$N%f!<%6!<$O!"3F7W;;5!$N>e$G!"C1FH$K%8%g&V$r<B9T$5$;$kDxEYKHI^CF$$F!"7W;;5!;q8;$rM-8z$KMxMQ7F$$kHO8@$$,$?$$!#

7W;;5!;q8;$rM-8z$K3hMQ9k$?$a$K!"C'<!4D6-$rBP>]H7$F3+H/$5l?%W%m%0%i%'$r<+F0E*$KJBNs2=9kJBNs2=%3%s%Q%$%i$,?tB?$/3+H/$5lF$$k!#8=:_$NJBNs2=%3%s%Q%$%i$NB?$/$OF1Ey$N=hM}G=NO$r;}$C$?7W;;5!$KhC$F9=@.$5lk6Q<A$J7W;;5!4D6-$rBP>]H7$F$$k!#6Q<A4D6-GOA4%W%m%;%C%5$KF1NL$N%?%9%/$r=hM}$5$;$k3HKhCF7W;;5!$N7W;;G=NO$r:GBg8B$K0z$-=P$9$3H,G-$k!#$7$+$7!"0lHIE*$J7W;;5!4D6-$NB?$/$O!"MM!9$J<dN'$N7W;;5!KhCF9=@.5l$kHs6Q<A$J7W;;5!4D6-G"$k!#Hs6Q<A7W;;5!4D6-$G$O!"7W;;5!$N%"!<%-%F%/%A%c$d!"3F%W%m%;%C%5$N@-G=$,0[$J$k!#$^$?!"$=li$N7W;;5!$r@\B3$9$k%M%C%H%o!<%/$b!"MM!9$JB.EYNbN,:.:_$7!"$=$N%H%]%m%8!<$bJ#;(G"$k!#$5iK!"%^%k%A%f!<%6!<4D6-2<GOB>$N%f!<%6!<%W%m%;%9$N1F6AKhCFMxMQ2DG=$J7W;;5!G=NO$,F0E*$KJQ2=$9$k!#

$=$N$?$a!"6Q<A4D6-KHfY!"Hs6Q<A4D6-GOF0E*$KJQ2=$9$k3F7W;;5!$NG=NO$K1~$8$F!"G[J,$9$k%?%9%/NL$rD4@0$7$J1l$P!"3F7W;;5!$N7W;;G=NO$r:GBg8B$K0z$-=P$9$3$HOG$-$J$!#$7$?$,CF!":#$^$G$NJBNs2=%3%s%Q%$%i$N%h$&$K%?%9%/$r6QEy$KG[J,$7$F$$F$O:GE,$JJBNs<B9T$OK>$aJJ$$!#

2f!9O3$N%h$&$J4D6-$KBP1~9k$?$a!"3F7W;;5!$N7W;;G=NO$K1~8F%?%9%/$rG[J,$9$kHs6Q<A4D6-8~$1JBNs2=%3%s%Q%$%i$hetero-TINPAR$r3+H/$7$F$$k!#$hetero-TINPAR$G$O!"<B9T;~$N7W;;G=NO$NUQ2=$KBP1~9k$?$a!"F0E*$KIi2Y$rJ,;6$9$k5!G=$rDs6!$7$F$$k!#7+7J$,$i!"=>MhNhetero-TINPARGO!"Ii2YJ,;65!G=$OHf3SE*C1=c$JbNG"$j!"3F7W;;5!$X$N%?%9%/3d$jEvF,=@FpGO$J$$!"F0E*Ii2YJ,;6$N%*!<%P!<%X%C%I$,Bg$-$$$J$LdBj$,$"$G$?!#$=N?$a!"8=<B$NMM!9$J4D6-$d%"%W%j%1!<%7%g&sKBP7$F!">o$K:GE,G"kH$O8@$$,$?$+G?!#

K\Js9p=qGO!"=@Fp$J%?%9%/3d$jEvFr2DG=$K$7!"$+$D!"F0E*Ii2YJ,;6$N%*!<%P!<%X%C%I$NDc8:9k<jK!$rDs0F$9$k!#$3lKhj!"hjB?$/$N4D6-$H%"%W%j%1!<%7%g&s$KBP1~9k3H,2DG=HJ$k!#

0J2<! "Bh2 >OGO! "=>Mh$NF0E*Ii2YJ,;6J}<0$r4^a?*hetero-TINPAR* $N35MW KD$$F=RYk! #Bh3 >OGOK\Js9p=q$GDs0F$9$kF0E*Ii2YJ,;6J}<0$K$D$$F=R Yk! #Bh4 >OGODs0F7?<jK!$NI>2A$r9T$$! "Bh5 >OG^Ha$k! #

2 *hetero-TINPAR* $N35MW

hetero-TINPAR GO! "Hs6Q<A4D6-$KBP1~$9k?aK! "Cj>]%W%m%;%C%5$H$$&35G0$rF3F~$7! "3N35G0$r1~MQ$7$F! "F0E*Ii2YJ,;6$r<B8=7F$$k! #K\>OGO! "Cj>]%W%m%;%C%5$HF0E*Ii2YJ,;65!G=$N35MWKD$$F=RYk! #

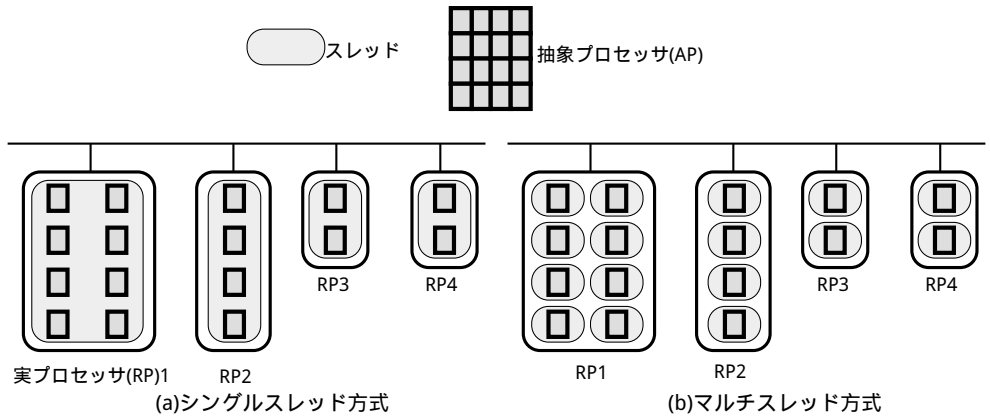
2.1 Cj>]%W%m%;%C%5

Hs6Q<A4D6-GO! "=hM}G=NO$N0[$J$k%W%m%;%C%5$K! "$=$N=hM}G=NO$K1~$8$?NL $NIi2Y$rJ,;6$5$;k3HKhC$F9bB.<B9T$,2DG=HJ$k! #$3N?$a! "6Q<A4D6-$KBP9kh&$J%V%m%C%/J,3d$d! "%5%$%/%j%C%/J,3d$JINC1=c$J5,B'E*$JJ,3d Kh$k%G! <%?$N3djIU1OG$-$J$$! #H3m,3liNJ,3d0J30NG0U$NJ,3d $r9T$C$?>l9g$O! "%G! <%?$r=jM-$9$k%W%m%;%C%5$NH=Dj<0$,C1=c$J<0KOJi$:! " <B9T;~$N%*! <%P! <%X%C%I$,Bg$-$/$J$k! #$=3G*hetero-TINPAR* GO! "6Q<A4D6-$N;~$N5,B'E*$J%G! <%?J,3d$Khk%G! <%?$N=jM-<IH=Dj$NC1=c5rHs6Q<A4D6-$K $*$$F$bMxMQ$9k?$a! "2>A[E*$JCj>]%W%m%;%C%5(Abstract Processors) $H$$&35G0$rF3F~$9$k! #$^$?! "%3%s%Q%$%i$N:G=*E*$J%3! <%I@8@.$NBP>]$HJk<B%W%m%;%C%5$r0J2<$Nh&$KDj5A$9$k! #

Cj>]%W%m%;%C%5 =hM}G=NO$,Ey$7$$MWAG%W%m%;%C%5$G9=@.$5l?2>A[E*JBNs7W ;;5!$rA[Dj$7! "$=$NMWAG%W%m%;%C%5$rCj>]%W%m%;%C%5$H8F$V! #%G! <%?$O! "3F Cj>]%W%m%;%C%5$K6QEy$KJ,3d5l$k! #Cj>]%W%m%;%C%5$N?t$O! "%f! <%6! <$, %=! <%9%W%m%0%i%`NCfG%G%#%l%/%F%#%V$N7A$GM?$($k! #

<B%W%m%;%C%5 %3%s%Q%$%i$,:G=*E*$J%3! <%I@8@.$NBP>]H9$kJ*M}E*$J%W%m%;%C %5$r<B%W%m%;%C%5$H8F$V! #<B9T;~$K$O! "<B%W%m%;%C%5$N=hM}G=NO$K1~$8$?8D?t$NCj>]%W%m%;%C%5$,G[J,$5lk! #

hetero-TINPAR GO! "<!$K=R$Y$kOwner Computes Rule $rMQ$$F$*j! "%G! <%?$O3FCj>]%W%m%;%C%5$K6Q<A$KJ,;6$5$l$F$$k! #$^$?! "1$D1$D$N%G! <%?$KBP 9k=hM}$O6Q<A$JbN$H2>Dj$9k?$a! "3FCj>]%W%m%;%C%5$N1i;=hM}NL$b6Q<A HJk3H,4|BTG-$k! #



?^2.1: <B%W%m%;%C%5GN%(%_%e%l!<%7%g%s$NJ}K!

Owner Computes Rule J,3d5l$?G[Ns%G!<%?$r=jM-9k%W%m%;%C%5$,$=$N%G!<%?$KBP9k;2>H$r9T$&J,$r<B9T$9kh$&$JSPMD(Single Program/Multiple Data)%3!<%I$r@8@.$9$k!#BeF~J8$G$O86B'$H7F:8JU$N%G!<%?$r=jM-9k%W%m%;%C%5$K3d$jIU1ilk!#

hetero-TINPAR $O!"Cj>]%W%m%;%C%5$N35G0$r1~MQ$7!"0J2<Nh$&$KHs6Q<A4D6-KBP9$k:GE,$JIi2YJ,;6r9$k!#

1. %G!<%?$rCj>]%W%m%;%C%5$K6Q<A$KJ,;6$5$;$k(%U%'!<%:1)
2. <B%W%m%;%C%5$N=hM}G=NO$KHfNc7?8D?t$NCj>]%W%m%;%C%5$r$=$N<B%W%m%;%C%5$KG[J,$9$k(%U%'!<%:2)
3. 6qBNE*$K!"$I$NCj>]%W%m%;%C%5$rIN<B%W%m%;%C%5$K3d$jIU1k$+7hDj$9$k(%U%'!<%:3)

%U%'!<%:1 GO!"6Q<A4D6-8~1NJBNs2=$r9T$&$@$1G"kN$G!"=>Mh$N6Q<A4D6-8~1N%3%s%Q%$%k<jK!$r$=$N$^$^MxMQ9k3H,G-$k!#

%U%'!<%:2 $H%U%'!<%:3 $G!"K\Js9p=q$NBP>]G"$kF0E*Ii2YJ,;65!G=$rDs6!9k!#3liK4X7F$OBh2.3@a$G>\=R9k!#

2.2 <B%W%m%;%C%5K*1kCj>]%W%m%;%C%5$N%(%_%e%l!<%7%g%s$NJ}K!

hetero-TINPAR GO!"0lDN<B%W%m%;%C%5KBP7$FJ#?t$NCj>]%W%m%;%C%5$,G[J,$5lk!#3F<B%W%m%;%C%5$O!"<+J,$KG[J,5l$?3FCj>]%W%m%;%C%5$K6Q<AG[J,5l$?%?%9%/$r=hM}9k!#3N3FCj>]%W%m%;%C%5r=l>$lFHN)$K07$&$+I&$+$G!"%7%s%0%k%9%l%C%IJ}<0$H%^%k%A%9%l%C%IJ}<0$H$$$&2DN=hM}J}<0$,9M$(il$k!#

%7%s%0%k%9%l%C%IJ}<0 3F<B%W%m%;%C%5KBP7$F%9%l%C%I$r1 D@$15/F0$7!"
3F%9%l%C%IFb$GJ#?t$NCj>]%W%m%;%C%5KBP9$k=hM}$r9T$&%3!<%I$r@8@.$9
$k!#$3$NJ}<0$G$O!"%9%l%C%IFb$G3FCj>]%W%m%;%C%5$N<B9T$9Y-%G!<%?NN
0hKBP9$k=hM}$N%9%1%8%e!<%j%s%0$rE,@Z$K9ToJ$$$H%G%C%I%m%C%/$r@8
8k2DG=@-$,$"$k!#$3N?$a!"%3%s%Q%$%i$OIT5,B'$J%G!<%?NN0h$rF0E*$K
07$($kh&$J%9%l%C%I$N@8@.$,I,MW$G$"$k!#
%^%k%A%9%l%C%IJ}<0 3F<B%W%m%;%C%5>e$K3d$jEvFil?Cj>]%W%m%;%C%51 $D
1 Dr!"$=$l$>$l%9%l%C%IH7$FN)$A>e2k!#F1$8<B%W%m%;%C%5$K3d$jIU
1il?Cj>]%W%m%;%C%54V$NDL?.$O!"%9%l%C%I4VDL?.H7$F<B8=$9$k!#$3
$NJ}<0$G$O!"3FCj>]%W%m%;%C%5$NFHN)@-$,9b$/!"3F%9%l%C%I$O6Q<A$J=hM}
r9k3HKJk$?$a!"%3%s%Q%$%i$O6Q<A$J=hM}$r9T$&$h$&$J%9%l%C%I$r
@8@.9l$PNI$$!#
%^%k%A%9%l%C%IJ}<0GO!"F10l$N%W%m%;%C%5$K3djIU1il$?Cj>]%W%m%;%C
%54V$N%G!<%?0\F0$O!"%9%l%C%I4VDL?.H7$F07$&$?$a!"%*!<%P!<%X%C%I$,Bg$-
$$!#FC$K!"Cj>]%W%m%;%C%5$NN3EY$r:Y$+$/$7$?>l9g$K$O!"$3$N%9%l%C%I4VDL?.
$NA}Bg$,82CxHJ$k!#$^$?!"<B9T;~$N%9%l%C%I@ZjBX($N%*!<%P!<%X%C%I$bLd
BjHJ$k!#$H3m$,!"%7%s%0%k%9%l%C%IJ}<0$G$O!"$3Nh$&$J%G!<%?0\F0$O<B
%W%m%;%C%5Fb$N%m!<%+%k$JBeF~J8K9k3H,G-k?$a!"Cj>]%W%m%;%C%5$N
N3EY$K4X$oi:%*!<%P!<%X%C%I$rDc/M^($k3H$,$G$-$k!#$^$?!"4{B8$NOS
$rMQ$$$k>l9gKO!"%7%s%0%k%9%l%C%IJ}<0KhCF!"1 DN%9%l%C%IFb$GHs6Q<A
$J%G!<%?$r=hM}9k$?$a$N%*!<%P!<%X%C%I$O!"OS $N2p:_$9$k%9%l%C%I4VDL?.$H
%9%l%C%I$N%9%1%8%e!<%j%s%0$r9T$&I,MW$N$"$k%^%k%A%9%l%C%IJ}<0$N%*!<%P!<
%X%C%Ihj0lHIE*$K>.$5$$!#0J>e$NM}M3$Khj!"*hetero-TINPAR GO!"Hs6Q<A
<B9T%9%1%8%e!<%j%s%0J}<0H7$F!"%7%s%0%k%9%l%C%IJ}<0$r:NMQ7F$$k!#

2.3 F0E*Ii2YJ,;65!G=

Hs6Q<A4D6-K*$$F!"9bB.$KJBNs<B9T$9k?aKO!"3F7W;;5!KBP7$F!"$=
$N=hM}G=NO$K1~8?E,@ZJNLN%?%9%/$r3d$j?6kI,MW,$"$k!#;vA0$K:GE,$J3F
7W;;5!$N=hM}G=NOHf$rM?$($ilJ$>l9g!"$3lr<+F0E*$K5a$a!"$=$l$K=>$C$F
Ii2YJ,;6$r9T$&I,MW$,$"$k!#$^$?!"3F7W;;5!$N=hM}G=NO$,F0E*$KJQ2=9k>l9g!"
3NJQ2=$KBP1~$9k?a$K!"F0E*Ii2YJ,;6$r9T$!";~4V$H6&$KJQF0$9$k7W;;5!
$NG=NO$KBP7F:GE,$J7W;NL$N3djEvFr9kI,MW,$"$k!#3lir<B8=9k

$?$a$K!"0J2<$N5!G=$,I,MW$HJk!#

%?%9%/J,;6Hf$N7hDj F0E*$KJQ2=9k7W;;5!4D6-$KBP1~$9k?aK!"8=:_$N7W

;;5!$NIi2Y$r<BB,$7!"$=lrbH$KE,@Z$J%?%9%/J,;6Hf$r5a$a$k!#

%?%9%/J,;6 5aail?%?%9%/J,;6HfrbHK!"<+F0E*$K3F%W%m%;%C%5$X$N!"%?

%9%/$N3d$jEvFrJQ99$9$k!#

F0E*Ii2YJ,;65!G=$rFCD'$E1k%Q%i%a!<%?H7$F!"IQEY$HJQ2=NL$,$"$k!#IQ

EYHO!"Ii2YJQF0Kh$k3F7W;;5!$N=hM}G=NCHf$NJQ2=$,Il$[$IKJlP!"<B

:]$KF0E*Ii2YJ,;6$r<B9T9k$+$H$$$&3H$G!"JQ2=NL$H$O!"3F7W;;5!$N=hM}G=

NCHf$NJQ2=$r%?%9%/$NG[J,Hf$KIl$[$IH?1G5;k+$H$$$&3HG"$k!#IQEY

b7$/$O!"JQ2=NLrBg-$/$9lP!"3F7W;;5!$N=hM}G=NCHf$NJQ2=$KBP$7!"%?%9%/

$NG[J,Hf$,h/DI=>9kh&KJ$k!#$7$+$7!"F1;~$KF0E*Ii2YJ,;6$N%*!<%P!<

%X%C%I$bA}Bg$9$k!#$^$?!"IQEY$r>e$2JQ2=NL$r>.5/9k$H!"%?%9%/$NG[J,Hf

$O!"3F7W;;5!$N=hM}G=NCHf$K=y!9$K6a$E$$$F$$/!#5U$K!"IQEY$r2<$2JQ2=NL$r

Bg$-$/9k$H!"3F7W;;5!$N=hM}G=NCHf$N>.$5$JJQ2=$OL5;k5l!"Bg$-$JJQ2=$,

H/@8$7$?H-$K!"%?%9%/$NG[J,Hf$O3F7W;;5!$N=hM}G=NCHf$K0l5$$K9go;il

$k!#0lHL$K!"3F7W;;5!$N=hM}G=NO$,7c7/JQ2=7F$$kH-$O!"3F7W;;5!$N=h

M}G=NCHf$K%?%9%/$NG[J,Hfr"$^$jDI=>7J$$h$&$K$7!"5)$K7+JQ2=7J$$

H-O9Pd$/DI=>$5$;$kh&K9kN$,$h$$!#

hetero-TINPAR GO!"F0E*$J%?%9%/$N:FJ,;6$r!"%W%m%0%i%`$N<B9TCf$K3F<B

%W%m%;%C%5XNCj>]%W%m%;%C%5$NG[J,$rJQ99$9$k3H$G<B8=$7$F$$k!#$^$?!"

hetero-TINPAR $O!"Owner Computes Rule $r:NMQ$7$F$$k$?$a!"Cj>]%W%m%;%C

%5$N:FG[J,$KO=lK3djEvFil$F$$k%G!<%?$NE>Aw$,H<$&!#0J2<$K*$$F!"

Cj>]%W%m%;%C%5$N0\F0$H$O!"Cj>]%W%m%;%C%5$K3djEvFil$F$$k%?%9%/$H%G!<

%?$r0\F0$5$;$k3H$r0UL#$9$k!#

hetero-TINPAR GO!"7W;;$K;22C$7$F$$kA4%W%m%;%C%5$,!"$"kDjail$?

;~E@$G!"6(D4$7$FIi2YJ,;6$r9T$&D4Jb6(D47?$NIi2YJ,;6@dN,$r:NMQ$7$F$$k!#

F0E*:FJ,;6$r9T$J$&COE@$G$"$k%A%"%C%/%]%$%s%H$N@_DjJ}K!5Z$S<B%W%m%;%C

%5$NG=NO$N4p=`HJ$kIi2Y>pJs$O0J2<NDLjG"$k!#

%A%"%C%/%]%$%s%H F0E*Ii2YJ,;6$9k+I&$+$rH=CG$7!"I,MW$J$i<B:]$KIi2Y

J,;6$r<B9T$9$k0LCV$r%A%"%C%/%]%$%s%H$H8F$V!#Cj>]%W%m%;%C%5$K3d$jEv

Fil?%?%9%/$N:G30%k!<%W$N1 %$%?%l!<%7%g%s$KBP1~9k<B%W%m%;%C%5

$N=hM}$,=*oC$?;~E@$H7F$$k!#9JoA"A4<B%W%m%;%C%5$,JBNs=hM}

$r0l;~Dd;_$7!"F14|2DG=$JE@$r%A%"%C%/%]%$%s%H$H7F$*$j!"3l0J30$N>l=j$O!"%A%"%C%/%]%$%s%H$K9k3HOG$-$J$$!#

hetero-TINPAR GO!"<B9T;~%*!<%P!<%X%C%I$rDc8:$9k?$a!"%7%s%0%k%9%l%C%LJ}<0$KhC$FJ#?t$NCj>]%W%m%;%C%5$N=hM}$r1DN%?%9%/H7$F=hM}$9$k!#$3$N:]!"<B%W%m%;%C%5>e$G$O!"J#?t$NCj>]%W%m%;%C%5$N=hM}$,M;9g5l$?7A$G9TolF*$j!"3FCj>]%W%m%;%C%5$NFHN)@-$O!"Hs>o$KDc$$$bNHJC$F$$$k!#7?$,$C$F!"G$0U$N;~E@$G0lIt$NCj>]%W%m%;%C%5$rB>$N<B%W%m%;%C%5$K0\F0$5$;k?aK$O!"Hs>o$K%*!<%P!<%X%C%INBg-$$$J#;($J=hM}$,I,MWHJ$k!#$3N?$a!"JBNs=hM}$NESCfJI$NF14|$r<hk3HNG-$J$$>l=jGNCj>]%W%m%;%C%5$N<B%W%m%;%C%54V$N0\F0$O9T$o$J$$!#

Ii2Y>pJs 0l$DA0$N%A%"%C%/%]%$%s%H$GG[J,5l$?Cj>]%W%m%;%C%5?t$H!"$=$N%A%"%C%/%]%$%s%H$+iN7W;;~4V$rIi2Y>pJs$H7FMxMQ9k!#3N7W;;~4VKO!"DL?.;~4V$dF0E*Ii2YJ,;6$N$?$a$N;~4V$O4^$^$J$$!#

2.4 =>Mh$NF0E*Ii2YJ,;65!G=$NLdBjE@

=>Mh$N*hetero-TINPAR* GO!"F0E*Ii2YJ,;65!G=$,!"Hf3SE*C1=c$J5!9=KhCF<B8=5l$F$$$?$,!"$=lG$O!"MM!9$J7W;;5!4D6-!"MM!9$J%"%W%j%1!<%7%g%s$KBP7F!">o$K:GE,$JIi2YJ,;6$,<B8=$5lF$$$kHO8@$$$,$?$$!#

LdBjE@H7FO!"0J2<Nh$&$JbN$,$"2ilk!#

1. Cj>]%W%m%;%C%5$N3dEvJ}<0$O!"C1=c$JO"B33dEv$N$_$,2DG=G"$k!#$3N?$a!"<B%W%m%;%C%5$NHV9f$H<B:]$N7W;;5!$NBP1~$Khk!"F0E*Ii2YJ,;6KMW9$k;~4V$X$N1F6A$,Bg$-$$!#
2. A4FN<B%W%m%;%C%5$KCj>]%W%m%;%C%5$r>/J/Hb1DOG[J,7J1lPJiJ$$!#3N$?$a!"Hs>o$K=hM}G=NO$Dc$$<B%W%m%;%C%5$,B8:_$7$?>l9g!"$=$N<B%W%m%;%C%5$KG[J,5l$?Cj>]%W%m%;%C%51$DJ,$N=hM}$N$?$a$K!"A4BN$N<B9T;~4V$,A}Bg$9$k!#
3. :FJ,;6N?aNIi2Y>pJs<}=8N?aK!"<B:]KO:FJ,;6$r9T$o$J$$$/Fb!"Bg$-$J%*!<%P!<%X%C%I$rH<$&A4<B%W%m%;%C%5$NF14|$,I,MWHJ$k!#

$=$3$G!"Bh3.1 @a$G!"1HV$NLdBjE@$KBP7F!"?7$?$K:G>.0\F0%3%9%HJ}<0Kh$kBP=h$rDs0F9k!#Bh3.2.2 @a$G2HV$NLdBjE@KBP7$F!"B>$K9bIi2Y$N%f!<%6!<%W%m%;%9,B8:_$9kJINM}M3KhCF!"=hM}G=NO,Dc$/$JCF$$$k<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,7J$$3HKhkBP=h$rDs0F$9$k!#Bh3.3 @a

$G3 HV$NLdBjE@KBP7$F!"<+N'Ii2YH=CGJ}<0$KhkBP=h$rDs0F$9$k!#

3 F0E*Ii2YJ,;65!G=$N2~NI

K\>OGO!"=>Mh$N*hetero-TINPAR*$NF0E*Ii2YJ,;65!G=KBP9$k2~NI$K$D$$F=RYk!#

3.1 E,1~7?Cj>]%W%m%;%C%5$N3dEvJ}<0

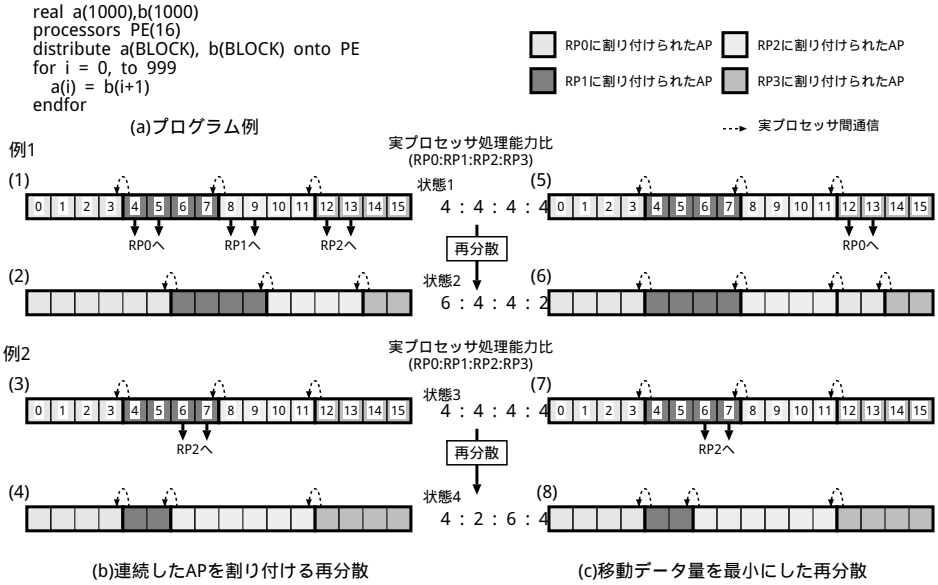
3.1.1 O"B33dEvJ}<0$H:G>.0\F0%3%9%HJ}<0

hetero-TINPAR$NF0E*Ii2YJ,;65!G=$G$O!"3F<B%W%m%;%C%5$KBP7FG[J,9kCj>]%W%m%;%C%5$N8D?t$r7hDj7?NA!"6qBNE*$K!"$I$NCj>]%W%m%;%C%5$NIN<B%W%m%;%C%5$K3d$jEvFk$+$r7hDj9k!#(0J2<!"G[J,9k$H3d$jEvFk$O!">e5-$N0UL#$G;HMQ$9$k!#)

Cj>]%W%m%;%C%5$r<B%W%m%;%C%5$X3djEvF$kJ}K!$K$O!"<B%W%m%;%C%5$NHV9f=g$KCj>]%W%m%;%C%5$NO"B3$7$?NN0h$r3d$jEvFF$$$/O"B3$7$?Cj>]%W%m%;%C%5$r3d$jEvFk<jK!(O"B33dEvJ}<0)$HF0E*:FJ,;6$KH<CFI,MWHJ$k<B%W%m%;%C%54V$NCj>]%W%m%;%C%5$N0\F0$rG-k@$1:o8:$9$k:FJ,;6$N;~$NDL?.%3%9%H$r:G>.$KM^$($k<jK!(:G>.0\F0%3%9%HJ}<0)$,9M$(il$k!#

O"B33dEvJ}<0HO!"<B%W%m%;%C%5$KCj>]%W%m%;%C%5$r3djEvFkH$-!"<B%W%m%;%C%5$NHV9f=g$KCj>]%W%m%;%C%5$NO"B3$7$?NN0h$r3d$jEvFF$$$/<jK!G"$k!#3F<B%W%m%;%C%5$,!"Cj>]%W%m%;%C%5r=$NG[J,Hf$K=>C?8D?t$:$DO"B3$7$F;}D3HKhj!"1i;;Cf$K@8$:$kNY@\$7$?Cj>]%W%m%;%C%54V$N%G!<%?%"%/%;%9$r<B%W%m%;%C%5Fb$N%m!<%+%k$JBeF~$KG-$k!#$3N?$a!"SOR$Nh&K"$k%G!<%?$r7W;;9kH-$KNY@\$9$k%G!<%?%W%m%0%i%`$N>19g!"1i;;~$N<B%W%m%;%C%54V$NDL?.NI$r8:$i$9$3H,G-$k!#H?LL!"$"$k<B%W%m%;%C%5$NCj>]%W%m%;%C%5$NG[J,?t$NJQ2=$,!"G[J,?t$OJQ2=7F$$$J$<B%W%m%;%C%5$NCj>]%W%m%;%C%5$N3d$jEvFK1F6A9k3H$,$"$k?$a!":FJ,;6;~$NCj>]%W%m%;%C%5$N0\F0$N%3%9%H$OA}2C9k!#

:G>.0\F0%3%9%HJ}<0HO!"F0E*:FJ,;6$N<B9T$KhjI,MWHJ$k<B%W%m%;%C%54V$NCj>]%W%m%;%C%5$N0\F0$rG-k@$1:o8:$9$k<jK!$G$"$k!#$=$N$?$a!"$"$k<B%W%m%;%C%5$KG[J,$5lF$$$kCj>]%W%m%;%C%5$O!"I,$:7bO"B3$7$?NN0h$r3d$jEvFilJ$$!#Cj>]%W%m%;%C%5$N0\F0$rCj>]%W%m%;%C%5$NG[J,?t$,JQ2=7?<B%W%m%;%C%5$N4V$GN_9T$&$3HGCj>]%W%m%;%C%5$N0\F0NL$rCj>]%W%m%;%C%5



?^3.1: :FJ,;6Kh$k3d$jIU$1<jK!

$NG[J,?t$NJQ2=J,N_$KM^$(k3H,G-$k!#

<B9T9k%W%m%0%i%'$K%k!<%W1?HB0MB8$,$"$k>19g!"8e$G=R$Y$kM}M3$Khj!":G>.0\F0%3%9%HJ}<0GO7c7@-G=Dc2<$,5/$3$k!#$=N?$a!"O"B33dEvJ}<0$NJ}$,$h$$!#$=$N$[$+$N>19g$K$O!":G>.0\F0%3%9%HJ}<0$r:NMQ9k$[$&$,$h$$!#

3.1.2 NcBj%W%m%0%i%'$rMQ$$$?N>J}<0$NF0:n2r@b

1. 0\F0%3%9%H$K4X$9$k2r@b

   0J2<$K?^3.1(a)$N%W%m%0%i%'rNcK7F3l$i2<jK!$K$D$$F=RYk!#?^3.1GO%G!<%?$,%V%m%C%/J,3d$KhjC j>]%W%m%;%C%5KBP7$FJ,;6$5lF$*j!"$3Nh$&$J%W%m%0%i%'$r<B9T$7$?;~$K!"3F<B%W%m%;%C%5$N@-G=Hf$,Ii2YJQF0Kh$j4:4:4:4(>uBV1)→6:4:4:2(>uBV2)$H$$$&C j>]%W%m%;%C%5$NG[J,?t$,A}Bg9k<B%W%m%;%C%5$H8:>/$9$k<B%W%m%;%C%5$,N%lF$$$k>19g$H!"4:4:4:4(>uBV3)→4:2:6:4(>uBV4)$H$$$&C j>]%W%m%;%C%5$NG[J,?t$,A}Bg9k<B%W%m%;%C%5$H8:>/$9$k<B%W%m%;%C%5$,NY$j9g$C$F$$$k>19g$N2DL$j$KJQ2=$9kNcK$D$$F9M$($k!#

   (a) O"B3E*$JC j>]%W%m%;%C%5$r3djEvF$k<jK!

      3N<jK!$O!"<B%W%m%;%C%5$KC j>]%W%m%;%C%5$r3d$jEvFkH-!"<B%W%m%;%C%5$NHV9f=g$KC j>]%W%m%;%C%5$NO"B3$7$?NN0h$r3djEvF$F$$$/<jK!G"$k!#

$^$?!"3N<jK!GO!"Cj>]%W%m%;%C%5$NG[J,Hf$,JQ2=7?H-!"G[J,?t$NA}$($?<B%W%m%;%C%5$H8:C?%W%m%;%C%5$N0LCV4X78$KhC$F!":FJ,;6$N;~4V$K1F6A$9$k!#?^3.1 $NNc2 Nh$&$K!"Cj>]%W%m%;%C%5$NG[J,?t$,A}Bg9k<B%W%m%;%C%5$H8:>/9k<B%W%m%;%C%5$,NY$j9gCF$$$k>l9g$NCj>]%W%m%;%C%5$rHJjN<B%W%m%;%C%5$K0\$9$@$1$G:Q$^3H$,B?$$$N$G!":G>.0\F0%3%9%HJ}<0$HHfYF!":FJ,;6;~4VO=l[IBg-$/$O$J$$$!#7+$7!"?^3.1 $NNc1 Nh$&$K!"Cj>]%W%m%;%C%5$NG[J,?t$,A}Bg9k<B%W%m%;%C%5$H8:>/9k<B%W%m%;%C%5$,N%lF$$$k>l9g$H!"Cj>]%W%m%;%C%5$rO"B3K9k?aK!"Cj>]%W%m%;%C%5rBg-$/0\F0$5$;$J$/$FOJiJ$$$?$a!":FJ,;6;~4V$,Bg$-$/A}2C9k!#

?^3.1(b) $NNc1 GN(1)→(2) $NA+0\$G$O!"RP0→RP1!"RP1→RP2!"RP2→RP3 $NCj>]%W%m%;%C%5$N0\F0O9YF2 8DHJCF$*$j!"A4BN$NCj>]%W%m%;%C%5$N0\F0$O6 8D$G$"$k!#Nc2 GN(3)→(4) $NA+0\$G$O!"Cj>]%W%m%;%C%5$N0\F0$ORP1→RP2 $N2 8D$N$_$HJC$F$$$k!#3Nh&$K!"Cj>]%W%m%;%C%5$NG[J,Hf$,JQ2=$7$?$H$-!"G[J,?t$NA}$($?<B%W%m%;%C%5$H8:$C$?%W%m%;%C%5$N0LCV4X78KhCF!"Cj>]%W%m%;%C%5$N0\F0NL$KBg$-$J:9$,=P$F$-$F$$$k!#

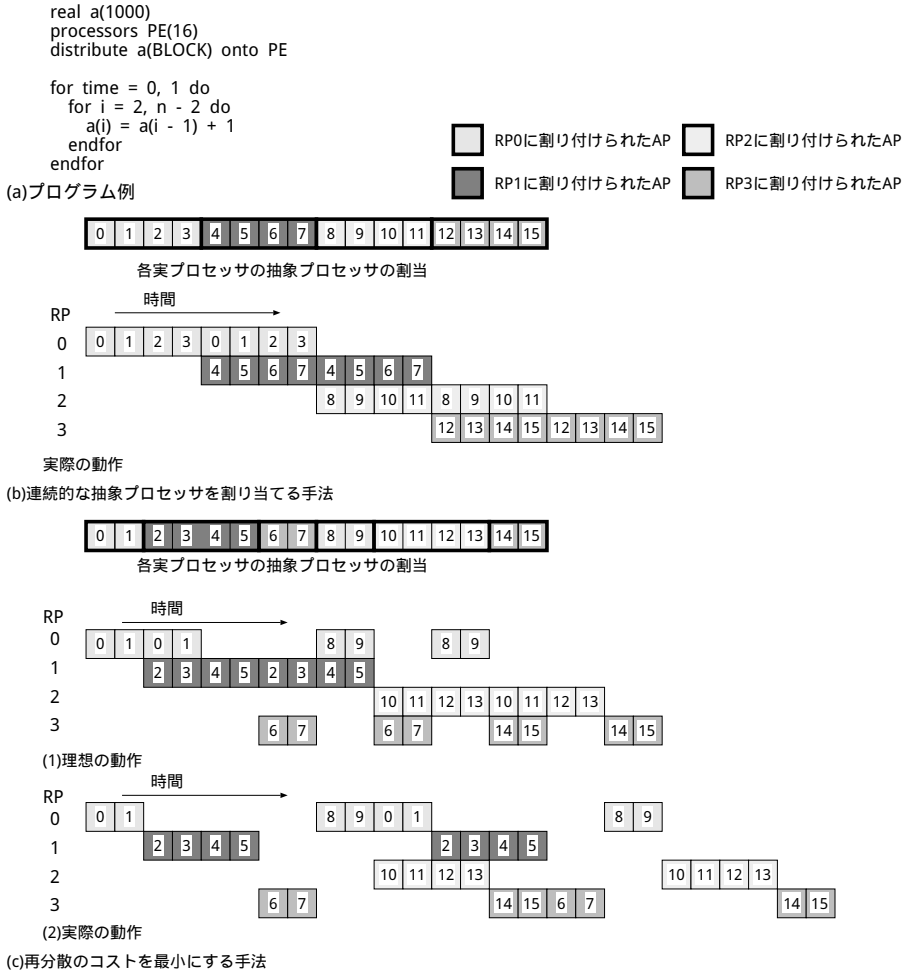
(b) :FJ,;6$N%3%9%H$r:G>.K9$k<jK!

3N<jK!$O!"F0E*:FJ,;6$N<B9TKhjI,MWHJk<B%W%m%;%C%54V$NCj>]%W%m%;%C%5$N0\F0rG$-$k$@$1:o8:9k<jK!G"$k!#

?^3.1(c) $NNc1 GN(5)→(6) $NA+0\$G$O!"Cj>]%W%m%;%C%5$N0\F0$ORP3→RP0 $N2 8D$N$_$HJCF*$j!"A4BN$NCj>]%W%m%;%C%5$N0\F0$O3 DG$"$k!#Nc2 GN(7)→(8) $NA+0\$G$O!"Cj>]%W%m%;%C%5$N0\F0$ORP1→RP2 $N2 8D$N$_$HJC$F$$$k!#Nc1!"Nc2 6&$KCj>]%W%m%;%C%5$N0\F0NL$O!"2 DKJC$F$$$F!"Cj>]%W%m%;%C%5$NG[J,Hf$,JQ2=7?H-!"G[J,?t$NA}$($?<B%W%m%;%C%5$H8:C?%W%m%;%C%5$N0LCV4X78$O!"Cj>]%W%m%;%C%5$N0\F0NL$K1F6A$rM?$($F$$J$$!#

2. %W%m%0%i%'$K%k!<%W1?HB0MB8$,$"$k>l9g

SOR Nh$&$J%W%m%0%i%'$G!"Wave Front 7?$NJUBNs<B9T$,9T$olk>l9g!":G>.0\F0%3%9%HJ}<0GO!"$=$N%W%m%0%i%'$NJUBNs@-$,H/4x5l$J$$!#?^3.2(a) $N%W%m%0%i%'$N<B9TNc$r?^3.2(b) $H(c) $K<($9!#?^3.2(b) $O!"O"B33dEvJ}<0$r:NMQ7?>l9g$N<B9TNc$G$"$k!#3NNcGO!"Cj>]%W%m%;%C%5$O



?^3.2: %W%m%0%i%`$K%k!<%W1?HB0MB8$,$"$k>l9g

$=$l$>$l4 D:$D=gHV$K<B%W%m%;%C%5$K3d$jEvFilF$$$C$F$$$k!#<B:]$N<B9T$G$O!"$^$:!"0 HV$N<B%W%m%;%C%5$,0 HV$+$i3 HV$NC;>]%W%m%;%C%5$N1 2sL\$NH?I|$r=hM}$7$?8e!"%G!<%?r1 HV$N<B%W%m%;%C%5$KE>Aw$9$k!#$=$N8e!"0 HV$N<B%W%m%;%C%5$O!"2 2sL\$NH?I|$N<B9T$r3+;O$7!"1 HV$N<B%W%m%;%C%5$O!"4 HV$+$i7 HV$NC;>]%W%m%;%C%5$N1 2sL\$NH?I|$N<B9T$r3+;O9k!#0J2<=g<!!"Wave Front 7?$NJUBNs<B9T$,9Tol$k!#

?^3.2(c) $O!":G>.0\F0%3%9%HJ}<0$r:NMQ7?>l9g$N<B9TNc$G$"$k!#3NNcGO!"0 HV!"1 HV!"8 HV$H9 HV$NC;>]%W%m%;%C%5$O0 HV$N<B%W%m%;%C%5$K!"2 HV$+$i5 HV$NC;>]%W%m%;%C%5$O1 HV$N<B%W%m%;%C%5$K!"10 HV$+$i13 HV$NC;>]%W%m%;%C%5$O2 HV$N<B%W%m%;%C%5$K!"6 HV!"7 HV!"14 HV$H15 HV$NC;>]%W%m%;%C%5$O3 HV$N<B%W%m%;%C%5$K3djEvFil$F$$$k!#?^3.2(c)(1) $O!"

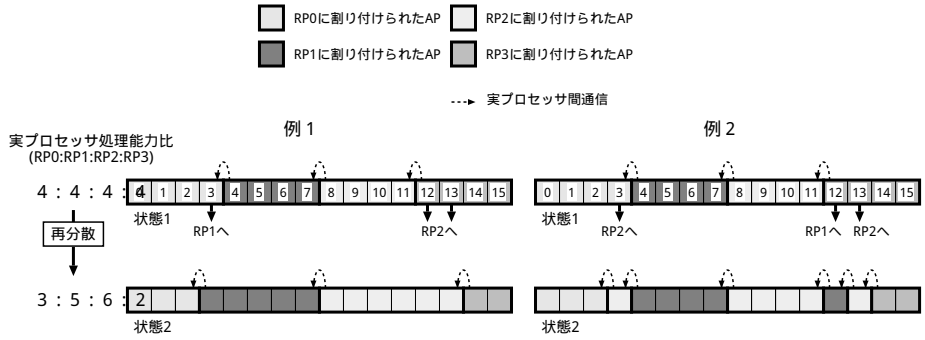
$=$NM}A[E*$J<B9T$NMM;R$r?^<($7$?$bNG$"$k!#0HV$N<B%W%m%;%C%5$O!"$^$:0HV$H1HV$NCj>]%W%m%;%C%5$N12sL\$NH?I|$N=hM}$r7?8e!"1HV$N<B%W%m%;%C%5$K%G!<%?$rE>Aw$9$k!#$=$N8e!"0HV$N<B%W%m%;%C%5$,8HV$H9HV$NCj>]%W%m%;%C%5$N12sL\$NH?I|$N=hM}$r9kKO!"3HV$N<B%W%m%;%C%5$+$i%G!<%?$r<u?.9kI,MW$,$"$k!#$3$N<u?.$NBT$A;~4V$K!"0HV$H1HV$NCj>]%W%m%;%C%5$N22sL\$NH?I|$N=hM}$r@h$K<B9T$9k3HKhj9bB.<B9T7F$$$k!#

7+$7!"Bh2.3@a$G=q$$$?h&$K!"*hetero-TINPAR$G$O!"1$D$N<B%W%m%;%C%5$K3djEvFil$F$$$kA4Cj>]%W%m%;%C%5rRHD$N%9%l%C%I$G=hM}7F$$$k$?$a!"F1$8<B%W%m%;%C%5$K3djEvFil$F$$$kA4FNCj>]%W%m%;%C%5$,!"JBNs2=$9k?aKJ,3d5l$F$$$k%k!<%W$r=hM}$7=*ok$^$G$O!"<!$N=hM}$K?J$`3HOG$-$J$$!#D^$j!"Cj>]%W%m%;%C%50HV!"1HV!"8HV$H9HV$,F1$8<B%W%m%;%C%5$K3djEvFil$F$$$k>19g!"Cj>]%W%m%;%C%50HV$H1HV$N22sL\$NH?I|$N=hM}$HCj>]%W%m%;%C%58HV$H9HV$N12sL\$NH?I|$N=hM}$O!"K\Mh$O$IAi$+$iGb<B9TG-kK$b4X$oi:!"3N@)LsKhCF8e<T$r@h$K7W;7J1lPJiJ$$!#7?$,$C$F!"$3$N@)Ls$N$?$a$K!"<B:]$NF0:n$O!"?^3.2(c)(2)$Nh&$K3F<B%W%m%;%C%5$,!"JBNs2=9k$?$a$KJ,3d$5lF$$$k%k!<%W$N<+J,$K3djEvFil$?Cj>]%W%m%;%C%5$N=hM}$,A4$F=*C?8e$K!"<!$N=hM}$K?J$`3HKJj@x5l$:!"<B9T;~4V$OBgI}$KA}2C$9$k!#

%^%k%A%9%l%C%IJ}<0$r:NMQ$9kH!">e5-$N@)Ls$OJ/Jk$?$a$K!"Cj>]%W%m%;%C%50HV$H1HV$N22sL\$NH?I|$N=hM}$HCj>]%W%m%;%C%58HV$H9HV$N12sL\$NH?I|$N=hM}$O!"IAi+iG$b2DG=$KJk!#7+$7!"$3$NLdBj$OO"B33dEvJ}<0$r:NMQ$9k3HKhj2sHrG-$k!#%^%k%A%9%l%C%IJ}<0$Khk%*!<%P!<%X%C%I$O!"O"B33dEvJ}<0$N%*!<%P!<%X%C%IhjBgI}KBg-$$$H9M$($ilk$?$a!"3NLdBj$r2r7h$9k?aK!"%^%k%A%9%l%C%IJ}<0$r:NMQ$9k3HO7J$$!#

3.1.3 :G>.0\F0%3%9%HJ}<0K*1kCj>]%W%m%;%C%5$N3dEvJ}?K

:G>.0\F0%3%9%HJ}<0Kh$k>19g$G$b!"2DG=$J8B$jCj>]%W%m%;%C%5$rO"B3$5$;$F3d$jEvF?J}$,!"1i;Cf$K@8$:$kNY@\$7$?Cj>]%W%m%;%C%54V$N%G!<%?%/%;%9$r%m!<%+%k$JBeF~K9k3$H,$G$-!"NY@\$7$?<B%W%m%;%C%5$KBP9kDL?.NL$r8:$i$9$3$H,$G$-$k!#^3.3$NNc1$G$O!"Cj>]%W%m%;%C%5$N0\F0$O!"*RP0→RP1



?^3.3: Cj>]%W%m%;%C%5$N6qBNE*$J3djEvFJ}

$N0\F0$,1 $DRP3→RP2 $N0\F0$O2 DHJC$F$$k!#Nc2 GO!"RP0→RP2 $HRP3→RP1 $HRP3→RP2 NN0\F0$,1 D:DHJC$F$$k!#Nc1!"Nc2 6& $KCj>]%W%m%;%C%5$N0\F0NL$CF1$8G"k,!"<B%W%m%;%C%54VDL?.$,I,MW$J8D=j $O!"Nc1 $,3 8D=j$JNKBP$7Nc2 GO6 8D=j$HG\$KJC$F$$k!#K\<jK!GO!" Cj>]%W%m%;%C%5$r2DG=$J8B$jO"B3E*$K3djEvFk?aK!"0J2<Nh$&&$J%"%k%4 %j%:%`$r:NMQ$7$?!#

1. Cj>]%W%m%;%C%5$NG[J,?t$,8:>/9k<B%W%m%;%C%5$K3d$jEvFilF$$kCj >]%W%m%;%C%5N&$A!"0lHVO"B3$7$F$$kHOOO$,69$$NN0h$rC5$9!#
2. 3NNN0hNHJj$NCj>]%W%m%;%C%5$,!"G[J,?t$,A}Bg$9$k<B%W%m%;%C%5$K 3djEvFil$F$$k>l9g!"$=$NCj>]%W%m%;%C%5B&$+$i=g$K<B%W%m%;%C%5$X $N3d$jEvFr2rJ|9k!#3djEvF$r2rJ|$9kH$O!"$I3K$b3d$jEvFi$l $F$$$J$>uBV$H9k3HG"$k!#
3. G[J,$,A}Bg$9$k<B%W%m%;%C%5$K3djEvFil$F$$kCj>]%W%m%;%C%5N&$A!" O"B3$7$F$$kHOOO$,:GBg$NNN0h$rC5$9!#3NNN0hNNYj$N3d$jEvFN2rJ| 5l$?Cj>]%W%m%;%C%5$,B8:_9k>l9g!"3NCj>]%W%m%;%C%5r=$N<B%W%m %;%C%5$K3djEvF$k!#
4. =g<!!"O"B3$7$F$$kHOOO$,<!$K>.$5$$NN0hNNYj$N3d$jEvFN2rJ|5l$? Cj>]%W%m%;%C%5$r$=$N<B%W%m%;%C%5$K3d$jEvFk!#3l$r!"G[J,?t$NA}Bg 9k<B%W%m%;%C%5$K3d$jEvFilF$$kCj>]%W%m%;%C%5NNYj$K!"3d$jEv FN2rJ|5l$?Cj>]%W%m%;%C%5$,J/Jk$^$G7+jJV9!#
5. 3djEvF$N2rJ|$5l?Cj>]%W%m%;%C%5$NHV9f=g$K!"$^$@3djEvF2DG=$J<B %W%m%;%C%5$X!"3djEvF$F$$/!#

3.1.4 C j>]%W%m%;%C%5$N3dEvJ}<0$N<+F0H=Dj

A0@a$G=R$Y$?$h$&$K!"C j>]%W%m%;%C%5$K3d$jEv$FJ}$K$O!":G>.0\F0%3%9%HJ}<0$HO"B33dEvJ}<0$,$"$k!#A0=R$NDL$j!"<B9T$9$k%W%m%0%i%\$K%k!<%Wl?HB0MB8$,$"$k>l9g!"O"B33dEvJ}<0$r:NMQ$7!"$=N[$+$N>l9g$O!":G>.0\F0%3%9%HJ}<0$r:NMQ7?J}$,$h$$!#

hetero-TINPAR GO!"%$%?%l!<%7%g%s4V$K0MB8$,$J$$>l9g!"DL?.$N:GE,2=$N$?$a!"$"$k%$%?%l!<%7%g%sFb$GAw=P9Y$-%G!<%?$N&$A!"$=$N%$%?%l!<%7%g%s$G@8@.$5lk%G!<%?0J30$N%G!<%?$O!":GE,2=$,@5$7$/9T$oll$P!"%$%?%l!<%7%g%s$N@hF,ItJ,$GAw?.5l$k!#$7$?$,CF!"%$%?%l!<%7%g%sFb$GAw?.9Y$-%G!<%?$NA4F,!"%$%?%l!<%7%g%s$N@hF,ItJ,$GAw?.$5lF$$k>l9g!"3N%G!<%?$K4X$7$F%k!<%Wl?HB$N0MB8$,$J$$$3H,o+$k!#:GE,2=$,@5$7$/9Tol$J$$>l9g!"%G!<%?$NAw?.$,%$%?%l!<%7%g%s$N@hF,ItJ,$G9T$olkh&KOJi$:!"%$%?%l!<%7%g%s4V$K0MB8$,J/Fb!"Wave Front 7?$NJBNs<B9T$KJk!#3N>l9g$b!"O"B33dEvJ}<0$r:NMQ7?J}$,$h$$!#%G!<%?$NAw?.$,%$%?%l!<%7%g%s$N@hF,ItJ,$G9T$olF$$kh&$J>l9g$K$O!":G>.0\F0%3%9%HJ}<0$r:NMQ9kh&$KH=Dj$7!"$=$&GJ$$>l9gKOO"B33dEvJ}<0$r:NMQ$9kh$&$KH=Dj9kh&K7$?!#

3.2 Ii2YG[J,$K4X$9$kogCM@)8f

3.2.1 C j>]%W%m%;%C%5$N0\F0$N@)8B

=>Mh$N*hetero-TINPAR* GOMW5a5l$?C j>]%W%m%;%C%5$NUQ2=NL$rH>8:[1]$5$;$F$$?$,!"C1=c$KJUQ2=NL$,%f!<%6!<$,;XDj7?ogCM0J2<$N>l9g$OJUQ2=5;$J$$$3HK9kJ}K!$bA*Br$G$-$kh&K7$?!#

3.2.2 C j>]%W%m%;%C%5$rG[J,$5lJ$J<B%W%m%;%C%5

=>Mh$N*hetero-TINPAR* GO!"3F<B%W%m%;%C%5$KBP$7>/J/Hb0lDOC j>]%W%m%;%C%5$rG[J,$9kI,MW,$"$C?$,!"C j>]%W%m%;%C%5,G[J,$5lk?t$,%f!<%6!<$,;XDj7?ogCMhj>/$J$$>l9g$O!"$=$N<B%W%m%;%C%5$KC j>]%W%m%;%C%5$rG[J,$7$J$$$h$&$K7?!#

=hM}G=NONDc7W;;5!$d!"B>$N%f!<%6!<%W%m%;%9KhCF9bIi2YKJCF$$$k7W;;5!$,4^$^lF$$$k>l9g!"$=$N7W;;5!$KC j>]%W%m%;%C%5$rG[J,9khj$b!"G[J,$;$:$KDL?.$N%*!<%P!<%X%C%I$r8:i7$?J}$,!"<B:]$N7W;;~4V$OC;$/$J$k

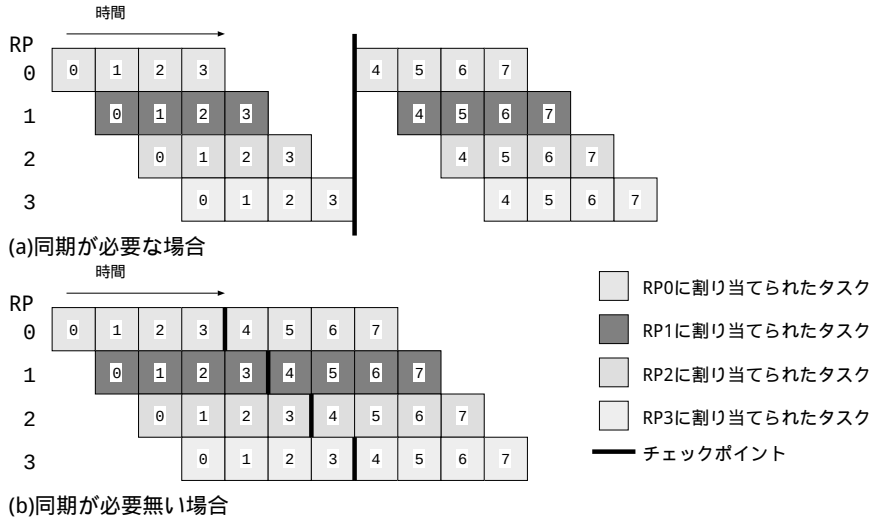
[1] 3NH>8:$OC<?t@Z$j<NFG9Tol$F$$$?$a!"MW5a$5l?JUQ2=NL$,1$N;~$O!"<B:]$K$OJUQ2=$5$;$J$$$3HKJC$F$$?!#

3H$,$"$k!#$^$?!"<B%W%m%;%C%5$N=hM}G=NOHf$,6K$aFBg-$/$JkH!"Cj>]%W%m%;%C%5$NN3EY$O8GDj5l$F$$k$?$a!"$=$NN3EY$,==J,:Y$+$/$J$$>19g!"Cj>]%W%m%;%C%5$NG[J,Hf$,<B%W%m%;%C%5$N=hM}G=NOHf$KBP1~G-$J$$>19g$,5/$3$jF@$k!#3Nh&$J>19g!"=hM}G=NO$NDc$$<B%W%m%;%C%5$K3d$jEvFil?Cj>]%W%m%;%C%5$N=hM}$K;~4VrMW9k?$a!"A4BN$N=hM}$,CY/$Jk3H,$"$k!#3Nh&$J>19g$O!"Ds6!2DG=$J=hM}G=NO$NDc$$<B%W%m%;%C%5KO!"Cj>]%W%m%;%C%5$rG[J,$7$J$$J}$,NI$$!#

K\<jK!GO!"Cj>]%W%m%;%C%5$,G[J,$5lk?t$,%f!<%6!<$,;XDj7?ogCMhj>/$J$$>19g$O!"$=$N<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,$7$J$$$h$&$K7?!#$?$@$7!"8=;~E@$G$O$$$G$?$s!"Cj>]%W%m%;%C%5$NG[J,$rCf;_7?<B%W%m%;%C%5$O!"$=$l0J8e!"Cj>]%W%m%;%C%5$NG[J,BP>]HOJi$J$$!#3l$O!"Bh2.3@a$G=RY?h&$K!"Cj>]%W%m%;%C%5$,G[J,5l$k?t$r7hDj9kKO!"Ii2Y>pJs$,I,MWIT2D7g$G$"$k$,!"$$$C$?$sCj>]%W%m%;%C%5$rG[J,$7$J$$$h$&$K9k$H:GJ,;6$N;~$NIi2Y>pJs$,F@il$J$$$?aG$"$k!#7?$,$C$F!"9bIi2Y$KJC$F$$$?<B%W%m%;%C%5$,!"B>$N%f!<%6!<%W%m%;%9$N=*N;$JIKhC$F860x$,<h$j=|$+$l!":F$S==J,$J=hM}G=NO$r;}Dh$&$KJCFb!"Cj>]%W%m%;%C%5$r:F$SG[J,9kh&K9k3HOG-$J$$!#

3.3 <+N'Ii2YH=CGJ}<0

hetero-TINPAR GO!":FJ,;6r9k+H]$+$rH=CG9k$@$1$G!"A4<B%W%m%;%C%5$N4V$GF14|$r<hCFB>$N<B%W%m%;%C%5$HDL?.r9kI,MW,$"$C$?$,!"8=:_$NCj>]%W%m%;%C%5$NG[J,Hf$,:GE,$G$"$k$+$I$&$+$NH=CG4p=`$r!"3F%A%'%C%/]%$%s%H$K*$$FA02s$N%A%'%C%/]%$%s%H$+$i$N7W;;~4V$r7WB,$7!"$=$N;~4V$,JQ2=$7$F$$k$+$I$&$+$H$9$k$3$H$K$h$j!"<+J,$N;}DIi2Y>pJs$@$1$G:FJ,;6$9$k$Y$-$+H]$+$NH=CG$r2DG=$K$7$?!#$3$l$K$h$j!":FJ,;6$NI,MW@-$NH=CG$N%*!<%P!<%X%C%I,Bg$-$$!#?^3.4(a)$K!"$3$N$h$&$J%W%m%0%i%`$N<B9TCf$KF14|$r<hC?>19g$N<B9T$NMM;R$r<(9!#$3$N?^$N%W%m%0%i%`$O!"$k<B%W%m%;%C%5$,$"$k%V%m%C%/$r=hM}9kKO!"1$DA0$NHV9f$N<B%W%m%;%C%5$,F1$8HV9f$N%V%m%C%/$N=hM}$r=*$($F$$kI,MW$,$"$k!#Bh3.1.2@a$N2$G@bL@$7$?$h$&$K!"Wave Front 7?$N



?^3.4: F14|$,I,MW$J>19g$HITMW$J>19g

JBNs<B9Tr9$k%"%k%4%j%:%`$r:NMQ7F$$k%"%W%j%1!<%7%g%sGO!"<B9T3+;O$+$i<B:]$KJBNsF0:n$5lkh&KJk^$G!"$*hSF14|E@$KA4$F$N<B%W%m%;%C%5$,E~C#9k$^$GKO!"$"$kDxEY$N;~4V$,$+$+kN$GF14|$rHk$?$SK3$N;~4V$,%*!<%P!<%X%C%IH7$F@Q$_=EJC$F$$/$+$iG"$k!#$7$?$,CF!"F14|$O2DG=$J8BjHiJ$$$[$&$,NI$$!#

F0E*Ii2YJ,;6$r<B8=$9kK$O!"A4$F$N<B%W%m%;%C%5$,!"8=:_$NCj>]%W%m%;%C%5$NG[J,Hf$,:GE,$G$J$$$3HrG'<1$7$J1lPJiJ$$!#$=$N$?$a!"=>Mh$N*hetero-TINPAR*$G$O!":FJ,;6$r9T$&$Y$-$+$NH=CG$N$?$a$K!"7k2L$H7F:FJ,;6$,9T$olJ$$>19gGb!"A4BN$GF14|$r<hkI,MW,$"$C$?!#$3lKBP$7!"K\<jK!$G$O!"8=:_$NCj>]%W%m%;%C%5$NG[J,Hf$,:GE,G"k+I&$+$NH=CG4p=`$r!"3F%A%"%C%/%]%$%s%HK*$$F!"A02s$N%A%"%C%/%]%$%s%H$+$i$N7W;;~4V$r7WB,$7!"$=$N;~4V$,JQ2=7F$$k$+H]$+$GH=CG$9$k!#

$"$k<B%W%m%;%C%5$N=hM}G=NO$,JQ2=9k$H!"$=$N<B%W%m%;%C%5$N7W;;~4V$,JQ2=$9$k!#$^$?!"$=$N<B%W%m%;%C%5$,DL?.$r9T$C$F$$k>19g!"$=$NJQ2=$OB>$N<B%W%m%;%C%5$N7W;;~4V$K$b1F6A$r$*$h$\$9!#F0E*Ii2YJ,;6$,9T$ol?8e$O!"Cj>]%W%m%;%C%5$NG[J,Hf$O:GE,$KJC$F$$k$?$a!"0lC6!"F0E*Ii2YJ,;6$,9T$ol?HG$O!"7W;;~4V$,JQ2=7F$$J$4V$O!"Cj>]%W%m%;%C%5$NG[J,Hf$O:GE,G"kH$$$&3H$,$G$-$k!#7?$,$C$F!"7W;;~4V$NJQ2=$,8!=P$5l?H-$K!"8=:_$NCj>]%W%m%;%C%5$NG[J,Hf$,:GE,GJ$/$JC?H7$F!":FJ,;6$r9T$&$h$&$K9l$PNI$$!#

$"$k<B%W%m%;%C%5$,:FJ,;6$,I,MWG"kHH=CG7?H-$O!"$=lrA4BN$KDL
CN9k!#3N;~$K!"<+J,$,:FJ,;62DG=$J;~E@$r;XDj9k!#3NDLCN$r<u$1<h$C
$?B>$N<B%W%m%;%C%5$O!"F1MM$K<+J,$,:FJ,;62DG=$J;~E@$rB>$N<B%W%m%;%C%5$K
DLCN9k!#3F<B%W%m%;%C%5$O!"<u$1<hC?:FJ,;62DG=$J;~E@$NCf$G!"01HV!"=h
M}$N?J$s$G$$kH3m^$G!"=hM}$r?J$a!#$=3G!"A4%W%m%;%C%5$GF14|$r<h$C
$F:FJ,;6$r3+;O9k!#

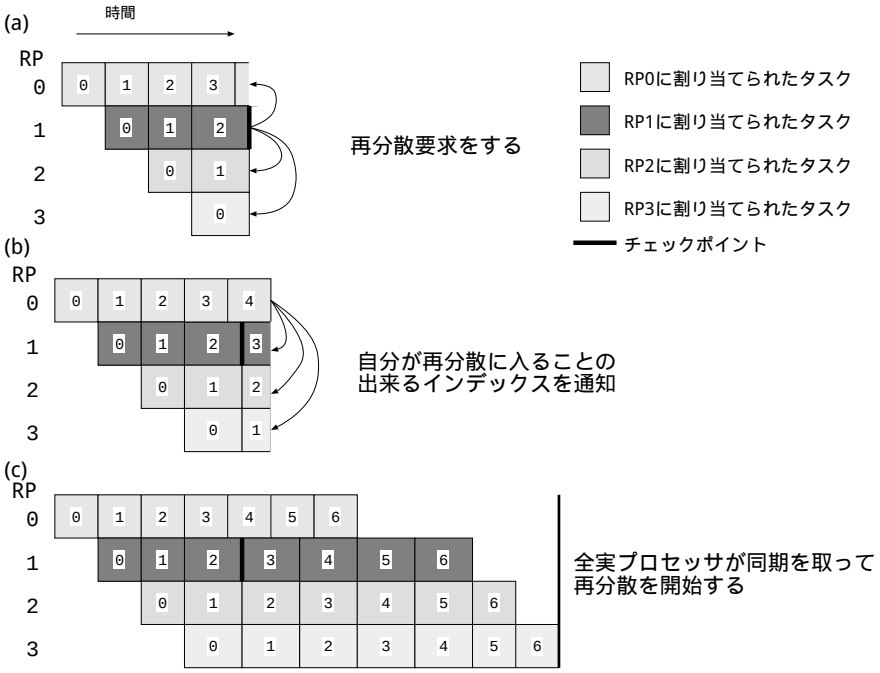
$^$?!"<B9T3+;OD>8e$O!"7WB,$5l?7W;;~4V$,JQ2=$7J/Fb!"Cj>]%W%m%;%C
%5$NG[J,Hf$,:GE,KJCF$$kHO8@$($J$$$?$a!":G=i$N%A%"%C%/%]%$%s%H$G
$O!"L5>r7o$GF0E*:FJ,;6r9k3HK7?!#

3N<jK!Kh$j!":FJ,;6$NI,MW@-$NH=CG$KF14|$,ITMW$KJj!"H=CG$N%*!<%P!<
%X%C%I$,6K$a$F>.$5$/$J$k!#?^3.4(b)$K!"Wave Front 7?$NJBNs<B9T$r9k%W%m
%0%i%`$N<B9TCf$KF14|$,ITMW$N>l9g$N<B9T$NMM;R$r<($9!#

$^$?!"=>Mh$O:FJ,;6$NI,MW@-$NH=CG$N$?$a$N%*!<%P!<%X%C%I$rDc8:9k$?$a
$K!"%A%"%C%/%]%$%s%H$rDL2a$9k?SKH=CGr9kNGOJ/!"%f!<%6!<$K;X
Dj5l$?IQEY$GH=CGr9k3HKhC$FH=CG$N2s?t$r8:$i7F$$$?$,!"Kh2sH=
CGr9k3H,2DG=KJC?!#3lKh$j!"Ii2Y$NJQ2=$KIR46$KH?1~7F:FJ,
;6r9k3H,2DG=KJC?!#

:FJ,;6$NI,MW@-$NHsF14|H=CG$N6qBNE*$J%"%k%4%j%:%`$O!"01J2<$NDLjG$"$k!#

1. 3F<B%W%m%;%C%5$,!"A02s$N%A%"%C%/%]%$%s%H$+iN7W;;~4V$r7WB,$72a5n
   $P2sJ,(8=:_P=3)$NJ?6Q$rHf3S$7$F!"D%0J>e(8=:_D=20)7W;;~4V$,A}2C$7$F$$$?i!"Ii2Y$,JQF0$7$?$bNH7F!":FJ,;6$,I,MW$G$"$k$HH=CG$9$k!#?^3.5$G$O!"1HV$N<B%W%m%;%C%5$,7W;;~4V$NA}2CKh$j:FJ,;6$,I,MW$HH=CG$9$k!#
2. :FJ,;6$,I,MW$@$HH=CG$7$?<B%W%m%;%C%5$O!"B>$NA4$F$N<B%W%m%;%C%5$K!":F
   J,;6MW5a$r=P$9!#:FJ,;6MW5a$HF1;~$K!"<+J,$,:FJ,;6$KF~k3HNG-$k
   ;~E@$bDLCN$9$k!#($3$N;~E@$O!"%A%"%C%/%]%$%s%H$rDL2a7?2s?t$G<($7!"
   01J2<%$%s%G%C%/%9$H9k)<+J,$,:FJ,;6$KF~k3HNG-$k%$%s%G%C%/%9
   $O!"A4BN$KDLCN9kNK<c43NCYl$,$"$k?$a!"8=:_$N=l$GOJ$/!"I8D
   @h(8=:_I=2)$N%$%s%G%C%/%9$r;XDj$9kh$&$K7F$$k!#?^3.5(a)GO!"
   1HV$N<B%W%m%;%C%5$,!"B>$NA4$F$N<B%W%m%;%C%5$K:FJ,;6MW5a$r=P$9!#$^
   $?!"1HV$N<B%W%m%;%C%5$,:FJ,;6$KF~k3HNG-$k%$%s%G%C%/%9G"$k
   4$bF1;~$KDLCN5l$k!#



?^3.5: :FJ,;6$NI,MW@-$NHsF14|H=CG

3. :FJ,;6MW5a$r<u$1<hC?<B%W%m%;%C%5$O!"<+J,$,:FJ,;6$KF~$k3HNG$-$k%$%s%G%C%/%9$rA4BN$KDLCN$9$k!#$3NH$-$N%$%s%G%C%/%9$bF1MM$K8=:_$+$iI8D@h$N%$%s%G%C%/%9$H7F$$k!#?^3.5(b) GO!"0 HV$N<B%W%m%;%C%5$,!"<+J,$,:FJ,;6$KF~k3HNG-$k%$%s%G%C%/%9G"$k6 $rA4BN$KDLCN9k!#B>$N<B%W%m%;%C%5$bF1MM$KDLCN$9$k!#

4. 3F<B%W%m%;%C%5$O!"B>$NA4FN<B%W%m%;%C%5$+$i!"%$%s%G%C%/%9$NDLCN$r<u$1<hk^GO!"$=$N$^$^=hM}$r?J$a$k!#$3$N;~$K!":#$^$G<u$1<h$C$?Cf$G!"bCHbBg$-$$%$%s%G%C%/%9$hjO@h$K?J$^$J$$$h$&$K9k!#

5. 3F<B%W%m%;%C%5$O!"B>$NA4FN<B%W%m%;%C%5$+$i%$%s%G%C%/%9$r<u$1<h$k$H!"$=NCfGbCHbBg$-$$%$%s%G%C%/%9$^$G!"7W;;$r?Jak!#3N$?$a!"3F<B%W%m%;%C%5$,A4BN$KDLCN9k%$%s%G%C%/%9$rDLCN9k;~E@NbNK9k$H!"$bCH$b?J$s$G$$$k<B%W%m%;%C%5$N>19g!"$=$N<B%W%m%;%C%5$,DLCN7?%$%s%G%C%/%9$,bCHbBg$-$$%$%s%G%C%/%9$KJk$,!"B>$N<B%W%m%;%C%5$+$i%$%s%G%C%/%9$NDLCN$r<u$1<hkN$,CY$lkH<+J,$,DLCN$7$?%$%s%G%C%/%9hj$b@h$K?JsG7^$$!":FJ,;6$KF~$kH-$N%$%s%G%C%/%9$,A4$F$N<B%W%m%;%C%5$GF10lGOJ/Jj!"7W;;$N@09g@-$,J]FJ$$!#?^3.5(c) GO!"0 HV$N<B%W%m%;%C%5$,DLCN7?6 $,!":GBg$N%$%s%G%C%/%9$JNG!"A4

FN<B%W%m%;%C%5$,!"6 $^$G=hM}$r?J$a$k!#

6. A4FN<B%W%m%;%C%5$,F1$8%$%s%G%C%/%9$N;~E@$G!":FJ,;6$r3+;O9k!#?^3.5(c) GO!"A4FN<B%W%m%;%C%5$,6 $^$G=hM}$,=*$C$?$H3m$GF14|$r<hCF:FJ,;6$KF~$k!#

4 @-G=I>2A

4.1 I>2A4D6-

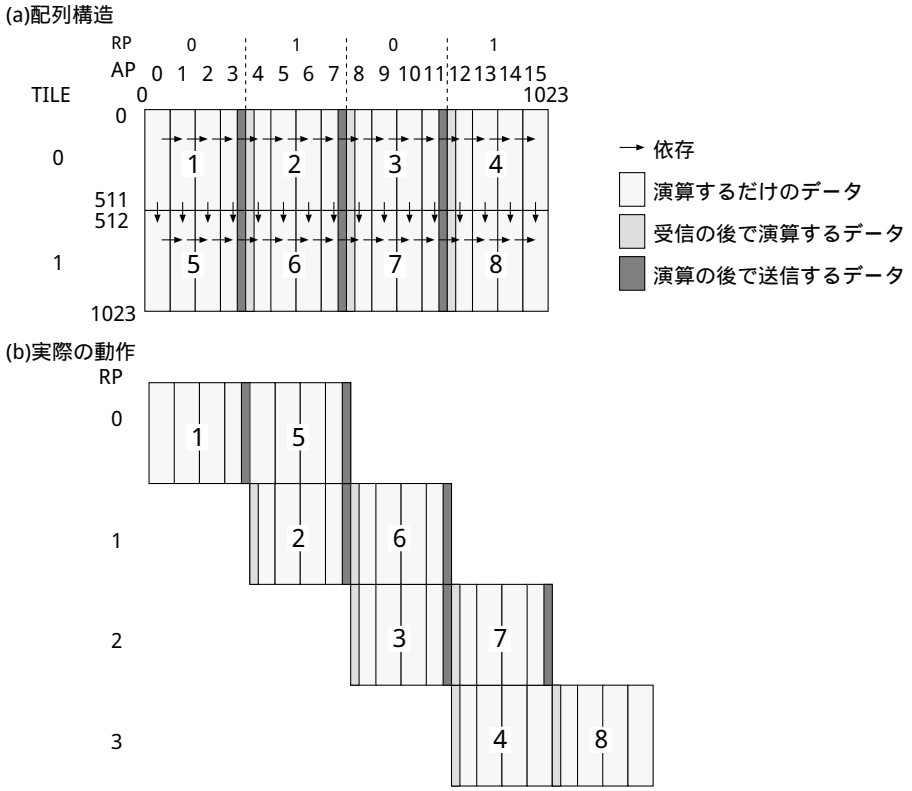
K\>OGO!"K\Js9p=q$G=R$Y$?F0E*Ii2YJ,;65!G=$N2~NIKhCF!"INDxEY$N9bB.2=$,G-$?$+$NI>2A$r9TC?!#

0J2<GO!"K\I>2A$KMQ$$$?%W%m%0%i%`!"7W;;5!4D6-KD$$F=RY?8e!"Bh3>O$G=R$Y$?F0E*Ii2YJ,;65!G=$N2~NI$NI>2A$r9T$&!#

4.1.1 I>2A%W%m%0%i%`

I>2A$K;HMQ$7$?%W%m%0%i%`$O!"SOR $HRed-Black SOR $N2<cN`$r;HMQ7?!#$$$:lbSOR K!Kh$k2<!85BJ1_7?JPHyJ,J}Dx<0$N5a2r%W%m%0%i%`G"$k!#$?$@$7!"*hetero-TINPAR* $N@-G=5sF0$NI>2A$KMQ$$$k$?$a<}B+H=Dj$O9T$o$:!"H?I|2s?t$rI>2A;~$K;XDj$9kbNH7?!#?^4.2 $H?^4.3 $K%j%9%H$r<($9!#;HMQ$7$?9TNs%5%$:$O1024×1024 G"$k!#FCK?@$7=q$-$NJ>l9g$O!"Cj>]%W%m%;%C%5$N8D?t$O128 8D$H7?!#

SOR $"$k%G!<%?$r7W;;$9kK$O!"$=$N%G!<%?$N>e$H:8$N$=$N%$%?%l!<%7%g%s$G7W;;:Q$N%G!<%?$rI,MW9k!#3N$?$a!"$"$kNs$N7W;;$,=*k^GO!"$=$N<!NNsN7W;;$,$G$-$J$$!#NcH7$F<B%W%m%;%C%5$,4 DN>l9g$r9M($k!#G[Ns$O!"?^4.1(a) Nh$&$K=D$K4 DKJ,3d5l$F3F<B%W%m%;%C%5$K3djEvFil$*$j!"3F%V%m%C/$NC<$GDL?.$,9T$olF$$$k!#3NDL?.$O!":8B&$N<B%W%m%;%C%5$,Aw?.$7!"1&B&$N<B%W%m%;%C%5$,<u?.9k$H$$$&N.lKJC$F$$$k!#$^$?!"hj:Y$+$/JBNs<B9T9k$?$a$K!"$3$NG[Ns$O%?%$%j%s0$,;\$5lF$$$F!"2#$K2 DKJ,3d5l$F$$$k!#?^4.1(b) K3$NG[Ns$r1H?I|9k>l9g$N<B:]$NF0:n$r?^<($7$?$bNr<($9!#<B:]$NF0:nGO!"0 HV0J30 $N<B%W%m%;%C%5$O!":8NY$N<B%W%m%;%C%5$+$i%G!<%?$r<u?.9k$^$G$O1i;;$r3+;O9k3H$,$G$-$J$$$?a!"$9$0KO1i;;$O3+;O$5lJ$$!#3Nh&$K!"SOR $OWave Front 7?$NJBNs<B9Tr9k?a!"3+;OD>8e$OJBNs<B9T$5lJ$$$?a!"5Z$SF14|E@$KA4%W%m%;%C%5$,E~C#$9k^GK;~4V$,$+$+$k$?a!"F14|$r<hC?H-$N%*!<%P!<%X%I$,Bg$-$$!#



?^4.1: SOR

Red-Black SOR G[Ns$NNsHV9f$H9THV9f$rB-$7$??t;z$,4q?t$N0LCV$N%G!<%?N_$r7W;;$7$?$"$H!"6v?t$N0LCV$N%G!<%?$r7W;;9k%"%k%4%j%:%`$G$"$k!#<B:]$N%W%m%0%i%`GO!"4q?tItJ,$H6v?tItJ,$rJ,N%7F2DNG[NsK7$F=hM}$r7F$$$k!#3N%"%k%4%j%:%`GO!"3F<B%W%m%;%C%5$O!"N>B&$N<B%W%m%;%C%5$+$i%G!<%?$r<u$1<hkI,MW,$"$k$?$a!"Wave Front 7?$NJBNs<B9T$r9kSOR Nh$&$K!"$"$k<B%W%m%;%C%5$,!"B>$N<B%W%m%;%C%5hj@h9T9k$H$$$&3HOJ$$!#

4.1.2 I>2A$K;HMQ$7$?7W;;5!4D6-

I>2A$O!"10Mbps $N%$!<%5%M%C%H%9$%C%A$Khj@\B3$5$l$?SPARCstation 20(0J2<SS20)4Bf!"SPARC Ultra-1(0J2<Ultra) 4Bf$HSPARC Classic(0J2<Classic)1BfKh$j9=@.$5l?4D6-K*$$$F:GBg4Bf9=@.$G9T$$!"86B'E*$K!"B>$N%f!<%6!<%W%m%;%9$NL5$$L5Ii2Y$N>uBV$GB,Dj$r9T$C$?[1]!#$^$?!"DL?.%i%$%V

[1] <B9T$N4D6-$O!"4pK\E*$KB>$N%f!<%6!<%W%m%;%9$NL5$$L5Ii2Y$N>uBV$G9TC?!#7+$7!"I>2A$K;HMQ7F$$$k7W;;5!N_$,!"%M%C%H%o!<%/$K@\B3$5$l$F$$$ko1GOJ/!"B??t$N7W;;5!$,%M%C%H%o!<%/$K@\B3$5lilF$$F!"$=$NJ+$+$i!"4vD+$N7W;;5!$rA*Br7F!"I>2A

```
const n = 1024
const n_time = 500
const tile_width = 512
real omega
real a(n,n)
processors AP(NAP)
distribute a(BLOCK,*) onto AP /* a() $O1<!85$a$G%V%m%C%/J,3d */

for time = 0, n_time - 1 remap 50 do /*H?I|(50 H?I|Kh$KF0E*Ii2YJ,;6)*/
  for outer_i = 0, n - 2, tile_width do
    for i = 1, n - 2 do
      /*  2<!85$a$K$OI}tile_width $N%?%$%j%s%0$r;\$9 */
      for j = MAX(1, outer_i), MIN(n - 2, outer_i + tile_width - 1) do
        a(i, j) = (a(i - 1, j) + a(i, j - 1) \
             + a(i, j + 1) + a(i + 1, j)) * (omega / 4) \
             + a(i, j) * (1 - omega)
      endfor
    endfor
  endfor
endfor
```

?^4.2: SOR

I=4.1: 3F%W%m%;%C%5$NC1BN@-G=

I>2A %W%m%0%i%`	7W;;5!	<B9T ;~4V[s]
SOR (2000 H?I|)	Ultra	534.9
	SS20	1576.4
	Classic	5216.8

%i%jH7$FMPI[2] $N<BAu=hM}7O$G$"$kMPICH[3] $r;HMQ$7$?!#

20 2sF1$8%W%m%0%i%`$N<B9T$r7+$jJV$7!"J,I[$NCf?4ItJ,$+$i7k2L$r5 $DCj=P$7!"$=$liNJ?6QrHCF<B9T7k2LH7$?!#

I=4.1 $K!"SS20!"Ultra!"Classic N=l>lK$D$$$FSOR $NC`<!<B9T;~4V$r<($9!#

$KMxMQ$7$?!#$=N?a!"I>2A$K;HMQ$7$?7W;;5!$OL5Ii2Y$N>uBV$rJ]C?$,!"F1$8%M%C%H%o!<%/KDJ,CF$$kB>$N7W;;5!$K$O!"B>$N%f!<%6!<$,:n6H$r7F$$?!#$^$?!"%U%!%$%k%5!<%P!<$JIN3F<o%5!<%P!<$bF1$8%M%C%H%o!<%/KDJ,CF$$k!#3liNMW0x$G!"%M%C%H%o!<%/$N>uBV$O>o$K0lDjGOJ/!"7W;;5!4V$N%G!<%?$NE>Aw;~4V$,0lDj$KOJi:!"<B9T7k2LKOBg$-$J8m:9$,=P$?!#

```
const n_cell = 1
const n=1024
const m=512
processors n_cell
real omega
real a(0:m-1:*,0:n-1) /* 6v?tItJ,$r3JG< */
real b(0:m-1:*,0:n-1) /* 4q?tItJ,$r3JG< */

for t = 0, 250 remap 25 do

for j =1, m-2 do
  for i = 1, m-2 do
     b(i,j*2  )=b(i,j*2  ) * (1-omega)  \
         + ( a(i,j*2-1)+a(i-1,j*2) + a(i  ,j*2)+a(i,j*2+1)) * (omega/4)
     b(i,j*2+1)=b(i,j*2+1) * (1-omega)  \
         + ( a(i,j*2-1)+a(i  ,j*2) + a(i+1,j*2)+a(i,j*2+1)) * (omega/4)
  endfor
endfor
for j =1, m-2 do
  for i = 1, m-2 do
     a(i,j*2  )=a(i,j*2  ) * (1-omega)  \
         + ( b(i,j*2-1)+b(i  ,j*2) + b(i+1,j*2)+b(i,j*2+1)) * (omega/4)
     a(i,j*2+1)=a(i,j*2+1) * (1-omega)  \
         + ( b(i,j*2-1)+b(i-1,j*2) + b(i  ,j*2)+b(i,j*2+1)) * (omega/4)
  endfor
endfor

endfor
```

?^4.3: Red-Black SOR

4.2 *hetero-TINPAR* KBP9$k2~NI$NI>2A

4.2.1 E,1~7?Cj>]%W%m%;%C%5$N3dEvJ}<0$NI>2A

Cj>]%W%m%;%C%5$N3d$jEvFN;~$N!"O"B33dEvJ}<0$H!":G>.0\F0%3%9%HJ}<0N=l>lr:NMQ$7?$H$-$N<B9T;~4V!"7W;;~4V!"DL?.;~4V!"5Z$S:FJ,;6;~4V$rHf3S$7!"N><jK!$NI>2A$r9T$C$?!#

I>2A4D6-$O!"SS20 2Bf$HUltra 2Bf$rMQ$$!"<B%W%m%;%C%5$NHV9f$rSS20!"Ultra!"Ultra!"SS20 $H$$&=gHV(0J2<SUUS) $G3d$j?6C?>19g$H!"Ultra!"Ultra!"SS20!"SS20 $H$$&=gHV(0J2<UUSS) $G3d$j?6C?>19g$N2DL$j$NHs6Q<A4D6-$H7?!#I>2A%W%m%0%i%'$O!"2000 H?I|$NSOR $H!"250 H?I|$NRed-Black SOR $r;HMQ$7$?!#

I=4.2 $K<B9T;~4V!"5Z$S$=$NFbLu$r<($9!#<B9T;~4V!"7W;;~4V!"DL?.;~4V!":FJ,;6;~4VO=l>$l!"%W%m%0%i%'$N<B9TKMW7$?;~4V!"<B9T;~4V$+$iDL?.;~4V$H:FJ,;6;~4V$r=|$$$?;~4V!"<B%W%m%;%C%54VDL?.KMW7$?;~4V!"F0E*Ii2YJ,;6

I=4.2: E,1~7?Cj>]%W%m%;%C%5$N3dEvJ}<0$NI>2A

;HMQ7? %"%k%4%j%:%`	7W;;5! $N=gHV	;HMQ <jK!	:G=* J,;6Hf	<B9T ;~4V[s]	7W;; ;~4V[s]	DL?. ;~4V[s]	:FJ,;6 ;~4V[s]
SOR	SUUS	:G>.	9:55:54:10	280.29	179.16	65.43	37.03
	SUUS	O"B3	9:55:55:9	284.15	183.12	63.94	39.90
	UUSS	:G>.	53:53:11:11	843.56	181.51	596.69	38.85
	UUSS	O"B3	53:52:12:11	360.75	181.41	71.16	109.86
Red-Black SOR	SUUS	:G>.	9:55:55:9	165.12	78.57	34.09	52.44
	SUUS	O"B3	9:55:55:9	165.61	75.83	32.49	57.24
	UUSS	:G>.	53:53:11:11	166.34	80.55	30.78	55.60
	UUSS	O"B3	54:52:11:11	187.03	78.66	27.82	80.66

$N<B9T$KMW7?;~4VG"$k!#;HMQ<jK!$N:G>.$HO"B3$O!"$=$l$>$l:G>.0\F0%3%9%HJ}<0$HO"B33dEvJ}<0$r<($9!#O"B33dEvJ}<0 3N<jK!GO!"<B%W%m%;%C%5$KCj>]%W%m%;%C%5$NO"B3$7$?NN0h$,3d$jEvFilF$$k!#F1$8<B%W%m%;%C%5$K3djEvFil$F$$kCj>]%W%m%;%C%54V$NDL?.$O!"<B%W%m%;%C%5Fb$N%m!<%+%k$JBeF~H9k3H,G-$k!#$3N?$a!"SOR Nh$&K"$k%G!<%?$r7W;;$9kH$-!"NY@\$7$?%G!<%?$rI,MWH9$k%W%m%0%i%`$G$O!"DL?.NI$OCc/M^$($ilF$$k!#DL?.;~4V$O!"Red-Black SOR GO!":G>.0\F0%3%9%HJ}<0KHfY10%$[$IDc/M^$($i$F$$k!#$^$?!"Cj>]%W%m%;%C%5$NG[J,?t$,A}$($k<B%W%m%;%C%5$H8:$k<B%W%m%;%C%5$,NY$j9gCF$$kSUUS KHfY$FN%$l$F$$kUUSS $N>19g$O!"Cj>]%W%m%;%C%5$rO"B3$K9k$?$a$KCj>]%W%m%;%C%5$rBg$-$/0\F0$5$;J/FOJi$J$$$?$a!":G>.0\F0%3%9%HJ}<0$KHf$Y!":FJ,;6;~4V$,Bg$-$/A}Bg7F$$k!#SUUS GO5%$+$i10%$[$IA}Bg7F$$k$@$1G"k,!"UUSS GO1.5G\$+$i2.5G\$[IKA}Bg7F$$k!#:G>.0\F0%3%9%HJ}<0 3N<jK!GO!":FJ,;6$N%3%9%H$r:G>.K9k?aK!"<B%W%m%;%C%5$K3d$jEvFilF$$kCj>]%W%m%;%C%5$NNN0h$O!">o$KO"B3E*$KOJCF$$ko1GO$J$$$#3N$?$a!"SOR Nh$&$K$"$k%G!<%?$r7W;;$9kH$-!"NY@\$7$?%G!<%?$rI,MWH9$k%W%m%0%i%`$G$O!"<B%W%m%;%C%54V$NDL?.$,A}Bg$7DL?.;~4V$,A}Bg$7$F$$k!#UUSS N[$&$,SUUS KHfY$F!"O"B33dEvJ}<0$H$NDL?.;~4V$N:9$,$o$:$+$KA}Bg$7$F$$k!#SOR GO!"Bh3.1.2@a$N2 $G@bL@$7$?M}M3$KhjUUSS NH$-$K!"DL?.;~4V$,8.5G\$[IKA}2C7F$$k!#SUUS $N;~$K$O!"$"$^$j$=$N1F6A$O=P$F$$J$$!#$^$?!"Cj>]%W%m%;%C%5$NO\F0$,:G>.8B$KM^$(il$F$$k$?$a!"Cj>]%W%m%;%C%5$NG[J,?t$,A}$($k<B%W%m%;%C%5$H8:$k<B

I=4.3: C j>]%W%m%;%C%5$rG[J,$5lJ$$<B%W%m%;%C%5$NI>2A

C j>]%W%m%;%C%5 $N8D?t	C j>]%W%m%;%C%5$rG[J, 7J$$h$&$K9kogCM	:G=*E*$J J,;6Hf	<B9T ;~4V[s]	7W;; ;~4V[s]	DL?. ;~4V[s]	:FJ,;6 ;~4V[s]
256	5	113:113:30:0	139.38	54.92	15.90	68.58
	0	114:114:23:5	136.28	43.50	26.83	64.17
128	2	57:57:14:0	139.06	53.97	15.19	69.91
	0	57:57:12:2	137.96	42.30	26.82	68.90
64	2	29:28:7:0	137.73	54.06	13.86	69.81
	0	28:28:6:2	132.95	43.78	21.17	68.06
32	1	14:14:4:0	133.65	56.06	12.63	64.96
	0	14:14:3:1	144.05	54.47	25.43	64.14
16	1	7:7:2:0	133.89	58.03	11.77	62.59
	0	6:7:2:1	162.62	63.64	25.68	67.85

%W%m%;%C%5$,NY$j9gCF$$$k SUUS $HN%$l$F$$$k UUSS $N:FJ,;6;~4V$N:9$O 5%$[IKM^$($ilF$$$k!#

4.2.2 C j>]%W%m%;%C%5$rG[J,$5lJ$$<B%W%m%;%C%5$NI>2A

Ultra 2 Bf!"SS20 1 Bf$H!"Classic 1 Bf$H$$$&9=@.$GI>2A$r9TC?!#I>2A%W%m %0%i%'$O!"500 H?I|$NSOR $r;HMQ$7!"C j>]%W%m%;%C%5?t$O256 8D!"128 8D!"64 8D!"32 8D!"16 8DN=l>lK$D$$FI>2A$r9T$C$?!#A4BN$NC j>]%W%m%;%C%5$, 256 8D$N>l9g$O!"C j>]%W%m%;%C%5$,G[J,?t$,5 $D0J2<$N>l9g!"A4BN$NC j>]%W%m %;%C%5$,128 8D$+64 8D$N>l9g$O!"C j>]%W%m%;%C%5$,G[J,?t$,2 $D0J2<$N>l9g!" A4BN$NC j>]%W%m%;%C%5$,32 8D$+16 8D$N>l9g$O!"C j>]%W%m%;%C%5$,G[J,?t$,1 DN>l9g$O!"A4$/G[J,7J$$$H7?!#

I=4.3 $KI>2A$N7k2L$r<($9!#C j>]%W%m%;%C%5?t$,!"32 8D$+16 8D$N>l9g$O!" Classic KO!"C j>]%W%m%;%C%5$rG[J,$7$J$$$J$,!"<B9T;~4V$,C;$/$JCF$$$k!# 3N7W;;5!$N9=@.$G$O!"Ultra $H Classic $NC j>]%W%m%;%C%5$NE,@5$JG[J,Hf$O!" Ls25:1 G"k,!"C j>]%W%m%;%C%5$,!"32 8D$H16 8D$N;~$NUltra $H Classic $NC j >]%W%m%;%C%5$NHf$O!"$=l>$l14:1 $H7:1 KJCF$*j!"Classic $KG[J,$5l?C j>]%W%m%;%C%5$N=hM}$K$+$+$k;~4V$,!"Ultra $KG[J,$5l?C j>]%W%m%;%C%5$N=hM}$K$+$+$k;~4V$h$jBgI}$KD9$/$KJC$F$$$k!#$=$N?$a!"A4BN$N<B9T;~4V$,C j >]%W%m%;%C%5$,32 8D$N;~$O8%!"16 8D$N;~$O20%$[$IA}Bg7F$$$k!#

C j>]%W%m%;%C%5$,64 8D0J>e$N;~$O!"Classic $KC j>]%W%m%;%C%5$rG[J,7?J} $,!"5U$KA4BN$N<B9T;~4V$,3%$[$IA}Bg7F$$$k!#

I=4.4: :FJ,;6$N4V3V$KhkJQ2=

:FJ,;6$N %A%%C%/$NJ}K!	:FJ,;6$N 4V3V	<B9T ;~4V[s]	7W;; ;~4V[s]	DL?. ;~4V[s]	:FJ,;6 ;~4V[s]
F14|	1	140.81	45.97	30.70	81.79
	5	109.52	46.33	18.59	48.21
	10	103.07	45.88	18.57	40.37
	50	101.91	47.48	18.97	35.74
HsF14|	1	97.68	44.45	17.10	35.97

$^$?!"Classic $KCj>]%W%m%;%C%5$rG[J,7J$>l9g$O!"<B%W%m%;%C%54VDL?.$,8:>/$9k?$a!"DL?.;~4V$,$[$\H>8:7F$$k!#Cj>]%W%m%;%C%5$,!"32 8D$H16 8D$N;~$O!"Classic $N=hM}G=NO$,Dc$$?aK!"%G!<%?$NAw?.$,CY$l!"$[$+$N<B%W%m%;%C%5$NDL?.BT$A$,A}Bg$9k?aK!"Cj>]%W%m%;%C%5$,64 8D0J>e$N;~KHfY!"Classic $KCj>]%W%m%;%C%5$rG[J,9k>l9gH7J>l9g$NDL?.;~4V$N:9$,Bg$-$/$JCF$$k!#

4.2.3 <+N'Ii2YH=CGJ}<0$NI>2A

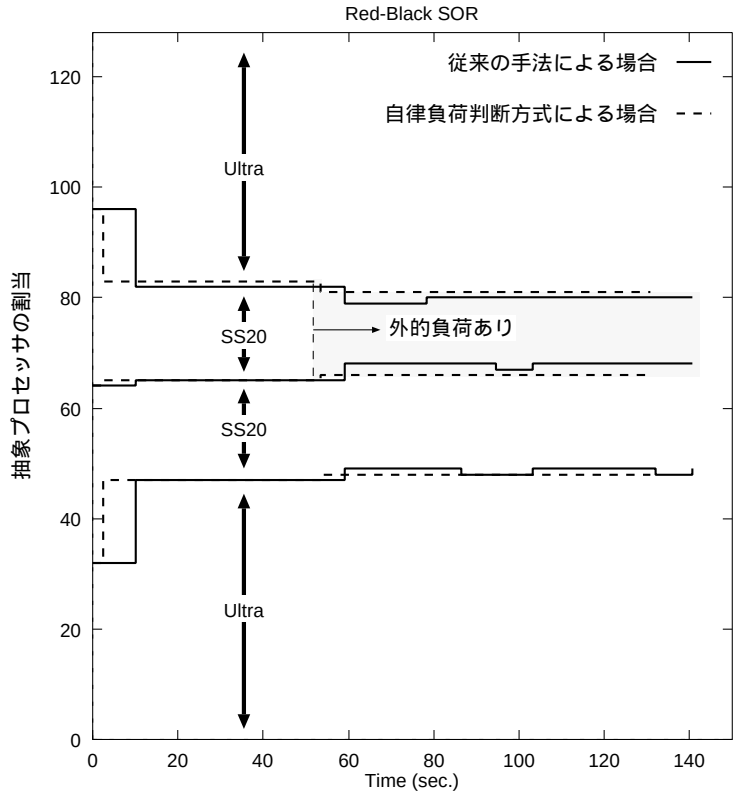
<+N'Ii2YH=CGJ}<0KhCF!":FJ,;6N9Y-$+H]$+$rH=CG$9kN$KF14|$,ITMWKJ$j!"%*!<%P!<%X%C%I$NDc2<7F$$k!#3lKhj!":FJ,;6$N%A%%C%/$rIQHK$K9T$&3H$,2DG=$KJk$?$a!"30E*Ii2YKh$k7W;;5!$N=hM}G=NO$KJQ2=$KBP7FIR46$KH?1~$7$F!"F0E*Ii2YJ,;6$r<B9T9k3H$,$G$-$kh&KJ$k!#$3$N8z2L$rD4Yk$?$a$K!"Ii2Y$,F0E*$KJQ2=$7J>l9g$H!"JQ2=$9$k>l9g$K$D$$FI>2A$r9T$C$?!#

Ii2Y$,F0E*$KJQ2=7J$>l9g Ultra $r2Bf$HSS20 $r2Bf$r;HMQ$7!"<B%W%m%;%C%5$NHV9f$rUltra!"SS20!"SS20!"Ultra $H$$&=gHV$G3d$j?6C?4D6-$GI>2A$7$?!#I>2A%W%m%0%i%'$O!"500H?I|$NSOR $r;HMQ$7$?!#:FJ,;6$NI,MW@-$NH=CG$N$?$a$KF14|$rHC$?$H$-$N%*!<%P!<%X%C%I$rI>2A$9k?aK!"F14|rI,MWH9k>l9g$N%A%%C%/$NIQEY$rJQ2=$5$;$?!#

I=4.4 $KI>2A$N7k2L$r<(9!#F14|$rI,MWH9$k=>Mh$N<jK!$N>l9g!"Kh2s%A%%C%/$r9k$H!"50 2s$K1 2s9T$&>l9g$KHfYF!":FJ,;6;~4V$O!"Ls2.3 G\$KJj!"<B9T;~4V$,Ls40%A}2C$7$F$$k!#HsF14|Kh$kH=CG$N>l9g$O!"Kh2s%A%%C%/$r9TCF$b50 2s$K1 2sF14|$r<h$C$F%A%%C%/$r9T$&>l9g$KHfYF!":FJ,;6;~4VCo$:$+G"k,A}Bg7F$$k$,!"F14|$r<h$k2s?t$N8:>/Kh$j!"<B9T;~4V$CLs3%C;=L5l$F$$k!#3lKhj!"HsF14|H=CG$N>l9g$NH=CGN?aN%*!<%P!<%X%I

I=4.5: F0E*:FJ,;6Kh$kIi2YJ,;6$NI>2A

:FJ,;6$N I,MW@-$N H=CG$N<jK!	:G=* J,;6Hf	EjF~7?%?%9%/$K H?1~$7$F:FJ,;6$r 3+;O7?;~4V(s)	:G=i$N %?%9%/$N <B9T;~4V(s)	ESCf$+$iEjF~7? %?%9%/$N <B9T;~4V(s)
=>Mh$N<jK!	48:18:15:47	59.03	141.54	377.36
HsF14 |H=CGKh$k<jK!	49:19:12:48	53.33	130.82	342.78



?^4.4: F0E*:FJ,;6Kh$kG[J,Hf$N?d0\

$O==J,$K>.$5$$$3H,<(5l$?!#

Ii2Y$,F0E*$KJQ2=9k>l9g Ultra $r2Bf$HSS20 $r2Bf$r;HMQ$7!"<B%W%m%;%C%5$NHV9f$rUltra!"SS20!"SS20!"Ultra $H$$$&=gHV$G3d$j?6G?4D6-$GI>2A$7$?!#$3$N4D6-$G!"2000 H?I|$NSOR(%?%9%/1) $r<B9T$5$;$?!#SOR $N<B9T$N52 IC8e $K3 $DL\$NSS20 KBP7$F!"C'<!4D6-MQ$N500 H?I|$NSOR(%?%9%/2) $r<B9T$5$;$?!#

I=4.5 $KI>2A$N7k2L$r<($9!#?^4.4 $K<B9TCf$NCj>]%W%m%;%C%5$NG[J,Hf$N?d0\$r<($9!#=>Mh$N<jK!GO!"59.03 IC$N;~E@$G:FJ,;6$r3+;O$7$F$$$k!#$=$l$KBP

7F!"<+N)Ii2YH=CGJ}<0GO!"53.38 IC$N;~E@$G:FJ,;6$r3+;O$7$F$$$k!#%?%9%/2 $N<B9T$KhkIi2Y$NJQ2=$O!"52 IC8e$KH/@8$9kN$G!"<+N)Ii2YH=CGJ}<0$G$O!"Ii2Y$,JQ2=9kH9$0$K$=$l$r46CN$7$FF0E*:FJ,;6$,<B9T5l$F$$$k!#$^$?!"%?%9%/1!"%?%9%/2 $N<B9T;~4V$O!"=>Mh$N<jK!$G$O!"$=l>$l141.54 IC$H377.36 IC!"HsF14|H=CGKh$k<jK!$G$O!"$=l>$l130.82 IC$H342.78 ICHJC?!#=>Mh$N<jK!$KHfYF!"HsF14|H=CGKh$k<jK!$G$O!"%?%9%/1!"%?%9%/2 6&$K8%$[$IAa$/$JCF$$$k!#

Ii2Y$NJQF0$KIR46KJC?3HKh$j!"%?%9%/1 $,!"%?%9%/2 $,<B9T$5lF$$$k<B%W%m%;%C%5$NIi2YG[J,$rB.d+$K8:>/$5$;$k3HKh$j%?%9%/2 $b8%$[IAa/JC$F$$$k!#

HsF14|H=CGKh$k<jK!$KhC$F!"Ii2Y$NJQ2=KBP7$F!"?WB.$KBP1~G-kh$&$KJj!"$=$lKhCF!"4{$KF0$$$F$$?%?%9%/!"ESCf$+$iEjF~7?%?%9%/$NN>J}$N<B9T;~4V$,C;=L$G$-$?3H$,<($5lF$$$k!#

5 $*$ojK

K\Js9p=qGO!"Hs6Q<A4D6-$rBP>]$H7?JBNs%3!<%I@8@.$r9T$&JBNs2=%3%s%Q%$%i*hetero-TINPAR*$NF0E*Ii2YJ,;65!G=$N2~NI$K$D$$F=RY?!#Cj>]%W%m%;%C%5$N3d$jEvFNJ}K!$r%"%W%j%1!<%7%g%s$KhC$F=@Fp$KJQ2=9k3H$,$G$-$kh&K7$?$3HKhj!"hjB?MM$J%"%W%j%1!<%7%g%s$KBP9k:GE,$JCj>]%W%m%;%C%5$N3djEvF$,2DG=$KJC$?!#$^$?!":FJ,;6$r9k$+$I$&$+$NH=CG$r!"F14|$r<h$iJ/Hb2DG=H7$?$3HKhC$F!"F0E*$KJQ2=9k7W;;!4D6-KBP7$F>/$J$%*!<%P!<%X%C%I$GBP1~G-kh$&$KJC$?!#$5iK%f!<%6!<$,:FJ,;64V3V$r;XDj9kI,MW$,$J$$$h$&$K7?!#

SOR $HRed-Black SOR $N%W%m%0%i%`$rMQ$$?@-G=I>2A$N7k2L!"K\<jK!$KhC$F!"Cj>]%W%m%;%C%5$N3dEvJ}<0$N2~NI$Khj!"=>Mh$N*hetero-TINPAR*$KHfYF!"10%$N@-G=8~>e$,<(5l$?!#<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,$7$J$$$3HKhC$F!"Cj>]%W%m%;%C%5$NN3EYHHfY!"7W;;!4V$K6KC<$J=hM}G=NO:9$,$"$k>19g!"15%DxEY$N@-G=8~>e$,<($5l?!#$^$?!"F0E*$JIi2YJQF0$KBP$7!"<+N'Ii2YH=CGJ}<0$KhjIi2YJQF0$r8!=P$9k3HKhj!"F0E*$KIi2Y$,JQF0$7$?>19g!"JQF0$7$?3F7W;;5!$N=hM}G=NOHf$K!"Cj>]%W%m%;%C%5$NG[J,Hf$rB.d+$K9g$o$;$k3H$,$G$-$kh&KJC?!#3lKh$j!"*hetero-TINPAR*$Khj%3%s%Q%$%k$5l?%W%m%;%95Z$S!"Ii2YJQF0$N860xHJC?%W%m%;%9$,6&$K10%DxEY

$N<B9T;~4V$NC;=L$,<($5l?!#

<UK-

K\8&5f$N5!2q$rM?$($F$/$@5j!"E,@Z$J8f;XF3$r;roC$?IYEDbC<#65<x$K?<?S$J<U0U$rI=7^$9!#

$^$?!"5.=E$J$4=u8@$r$$?$@$$?79bC0lO:=u65<x!"8^Eg@5M5=u<j$K?<$/46<UCW7^$9!#

5i$K!$6&F18&5f<TG"$k7&ED>;;K;a!"C$L&>08c;a!"EDCfMxI';arO8aH7$F!$F|:"$+$i8fJ\Z%2<5C$?5~ETBg3XBg3X1!9)3X8&5f2J>pJs9)3X65<<IYED8&5f<<$N=t7;$K46<UCW7^$9!#

;29MJ88%

[1] 8eF#?5Li!Hs6Q<A7W;;4D6-8~$1JBNs2=%3%s%Q%$%ihetero-TINPAR!"5~ETBg3X=$;NO@J8(1997)

[2] Message Passing Interface Forum: MPI: Message-Passing Interface Standard(1995)

[3] Bridges,P.,Doss,N.,Gropp,W.,Karrels,E.,Lusk,E. and Skjellum,A.: Users' Guide to MPICH, a Portable Implementation of MPI, Argonne National Laboratory

[4] Hans Zima/Barbara Chapman,Ph.D. B<2,MN0lLu: Supercompilers for Parallel and Vector Computers/%9!<%Q!<%3%s%Q%$%i,%*!<%'<R(1995)

[5] 3^86GnFA: JBNs=hM}5;=Q,%3%m%J<R(1991)

[6] R.S.Varga, =BC+@/><Lu 7W;;5!Kh$kBg7?9TNs$NH?I|2rK!,%5%$%(%s%9<R(1972)

[7] >.9qNO,B<ED7rO/,;09%=SO/,Dongarra Jack J.,D9C+@n=(I':9TNs7W;;%=%U%H%&%'%"WS,%9!<%Q!<%3%s,JBNs7W;;5!,4]A13t<02q<R(1991)

IUO?

A.1 $=$NB>$N%"%W%j%1!<%7%g%s$KhkI>2A7k2L

Bh4>OGO!";HMQ7J$+$C$?%"%W%j%1!<%7%g%s$G$"$k9TNs@Q$rMxMQ$7$?I>2A$r9k!#

9TNs@Q 2<!859TNsa(),b() $N9TNs@Qc() $r5a$a$k%W%m%0%i%'$G$"$k!#?^A.1 $K%j%9%H$r<(!#9TNs%5%$%:$O512×512 G"$j!"a(),c() $O!"$HbK1<!85J}8~$K%V%m%C%/J,3d$r9T$&!#b $O%m!<%+%k$G;}CF$$k$?$a!"DL?.$OH/@8$7$J$$!#

Cj>]%W%m%;%C%5$N3d$jEvFN;~$N!"O"B33dEvJ}<0$H!":G>.0\F0%3%9%HJ}<0N=l>lr:NMQ7?H-$N<B9T;~4V!"7W;;~4V!"5Z$S:FJ,;6;~4V$rHf3S$7!"N><jK!$NI>2A$r9TC?!#

I>2A4D6-$O!'SS20 2Bf$HUltra 2Bf$rMQ$$!'<B%W%m%;%C%5$NHV9f$rSS20!'Ultra!'Ultra!'SS20 $H$$&=gHV(0J2<SUUS) $G3d$j?6C?>19g$H!'SS20!'SS20!'Ultra!'Ultra $H$$&=gHV(0J2<SSUU) $G3d$j?6C?>19g$N2DL$j$NHs6Q<A4D6-$H7?!#

I=A.1 $K<B9T;~4V!"5Z$S$=$NFbLu$r<(!#<B9T;~4V!"7W;;~4V!":FJ,;6;~4VO=l>$l!"%W%m%0%i%'$N<B9TKMW7$?;~4V!"<B9T;~4V$+$i:FJ,;6;~4V$r=|$$$?;~4V!"F0E*:FJ,;6$N<B9T$KMW7?;~4VG"$k!#;HMQ<jK!$N:G>.$HO"B3$O!"$=$l$>$l:G>.0\F0%3%9%HJ}<0$HO"B33dEvJ}<0$r<(!#

O"B33dEvJ}<0 3N<jK!GO!"<B%W%m%;%C%5$KCj>]%W%m%;%C%5$NO"B3$7$?NN0h$,3d$jEvFilF$$k!#SUUS KHfY$FN%$l$F$$kSSUU $N>19g$O!"Cj>]%W%m%;%C%5$rO"B3$K9k?aKCj>]%W%m%;%C%5rBg-$/0\F0$5$;$J$/$FOJiJ$$$?$a!":G>.0\F0%3%9%HJ}<0$KHf$Y!":FJ,;6;~4V$,Bg$-$/A}Bg7F$$k!#SUUS GOLs5%A}Bg7F$$k$@$1G"k,!"SSUU GOLs1.7G\$KA}Bg7F$$k!#:G>.0\F0%3%9%HJ}<0 3N<jK!GO!"Cj>]%W%m%;%C%5$N0\F0$,:G>.8B$KM^$(il$F$$k$?$a!"Cj>]%W%m%;%C%5$NG[J,?t$,A}$($k<B%W%m%;%C%5$H8:$k<B%W%m%;%C%5$,NY$j9gCF$$kSUUS $HN%$l$F$$kSSUU $N:FJ,;6;~4V$N:9O[HsIJ$$!#

```
const n = 512
processors  AP(NAP)
real a(n,n), b(n,n), c(n,n)
distribute a(BLOCK,*) onto AP /*  a(), c() $O1<!85$a$G%V%m%C%/J,3d */
distribute c(BLOCK,*) onto AP

for i = 0, n - 1 do
  for j = 0, n - 1 do
    c(i, j) = 0.0
    for k = 0, n - 1 do
      c(i, j) = c(i, j) + a(i, k) * b(k, j)
    endfor
  endfor
endfor
```

?^A.1: 9TNs@Q

I=A.1: E,1~7?Cj>]%W%m%;%C%5$N3dEvJ}<0$NI>2A(9TNs@Q)

7W;;5!$N =gHV	;HMQ <jK!	<B9T ;~4V	7W;; ;~4V	:FJ,;6 ;~4V
SUUS	:G>.	88.87	63.29	29.35
SUUS	O"B3	86.76	63.35	27.00
SSUU	:G>.	89.60	63.28	29.63
SSUU	O"B3	107.98	63.23	46.93