Hs6Q<A4D6-8~$1JBNs2=%3%s%Q%$%i ***hetero-TINPAR***

— F0E*Ii2YJ,;6J}<0$N2~NI —

ED Cf ?5 ;J[†] 8e F# ?5 Li[††] 7& ED >; ;K[†††]
8^ Eg @5 M5[†††] ?9 bC 0l O:[†††] IY ED bC <#[†††]

K\9FGO!"hM}@-G=$N0[$J$k7W;;5!$,@\B3$5$l$?Hs6Q<A4D6-8~$1$NJBNs2=%3%s%Q%$%i *hetero-TINPAR* $,@8@.$9$k%3!<%I$KAH$_9~$^l?!"<B9T;~$NF0E*Ii2YJ,;6J}<0$K$D$$$F=RYk!#K\F0E*Ii2YJ,;6J}<0GO!"%k!<%W$N%$%?%l!<%7%g%s$r<B9T;~$K3F7W;;5!$N=hM}G=NO$K1~8F3djEvF$kJ}<0$rHC$F$$$k$,!"1) O"B3$7$?%$%?%l!<%7%g%s7+3djEvFk3H,G-$J$$!"2) @-G=NDc$$7W;;5!Kb:GDc8B$N%$%?%l!<%7%g%s$r3d$jIU1kI,MW$,$"$j!"$=$N7W;;5!$?aKA4BN$N<B9T@-G=$,Dc2<9k!"3) =hM}$N3d$jEvFNJQ99$NM-L5$rH=CG9k$?$a$KA4%W%m%;%C%5$,F14|rHkI,MW,$"$k$H$$$&LdBjE@$,$"C?!#3l$i3$D$NLdBjE@$r2~NI7?7k2L!"$=$l$>$lLs10%!"15%!"10%$N@-G=8~>e$,F@il$?!#

hetero-TINPAR: A Parallelizing Compiler for Heterogeneous Computing Environment

— Improvement of the Dynamic Load Balancing Scheme —

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In this report, we present the dynamic load balancing scheme at run-time embedded in the code generated by parallelizing Compiler *hetero-TINPAR*, which is oriented to heterogeneous computing environment where computers with different available computing power are connected. In this scheme, iterations of loops in the program are assigned to the processors at run-time. In the conventional scheme, 1)iterations must be assigned to the processors contiguously, 2)at least the minimum amount of tasks must be assigned to each processor even if the processor has the extremely small computing power, which degrades the total performance and 3)all processors must join the barrier synchronization to check the necessity of the load balancing among the processors. By the improvement of these drawbacks, we can achieve the improvement of performance by 10%, 15% and 10% respectively.

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$$$kHO8@$$$,$?$$!#

MM!9$J<oN`$N7W;;5!KhCF9=@.5l$kHs6Q<A$J7W;;5!4D6-GO!"7W;;5!$N%"!<%-%F%/%A%c$d!"3F%W%m%;%C%5$N@-G=$,0[Jk!#$^$?!"$=$liN7W;;5!$r@\B3$9$k%M%C%H%o!<%/$b!"MM!9$JB.EY$NbN$,:.:_$7!"$=$N%H%]%m%8!<$bJ#;($G$"$k!#5i$K!"%^%k%A%f!<%6!<4D6-2<$G$OB>$N%f!<%6!<%W%m%;%9$N1F6A$KhC$FMxMQ2DG=$J7W;;5!G=NO$,F0E*$KJQ2=9k!#

$=$N$?$a!"F0E*$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$$!#2f!9O3Nh$&$J4D6-$KBP1~$9k?$a!"3F7W;;5!$N7W;;G=NO$K1~$8$F%?%9%/$rG[J,9kHs6Q<A4D6-8~$1JBNs2=%3%s%Q%$%i *hetero-TINPAR* $r3+H/$7$F$$$k!#

hetero-TINPAR GO!"<B9T;~$N7W;;G=NO$NJQ2=$KBP1~$9k?$a!"F0E*$KIi2Y$rJ,;6$9$k5!G=$rDs6!7F$$$k!#7+7J$,$i!"=>Mh$N *hetero-TINPAR* GO!"Ii2YJ,;65!G=$OHf3SE*C1=c$JbNG"$j!"3F7W;;5!$X$N%?%9%/3d$jEvF,=@FpGO$J$$!"F0E*Ii2YJ,;6$N%*!<%P!<%X%C%I$,Bg$-$$$JINLdBj$,$"C?!#$=$N$?$a!"8=<B$NMM!9$J4D6-$d%"%W%j%1!<%7%g%s$KBP7F!"

[†] 5~ETBg3X9)3XIt
Faculty of Engineering, Kyoto University

[††] =;M'EE5$9)6H!3t!K
Sumitomo Electric Industries, Ltd

[†††] 5~ETBg3XBg3X1!9)3X8&5f2J
Graduate School of Engineering, Kyoto University

>o$K:GE,$G$"$kHO8@$$$,$?$+C?!#

K\8&5fGO!"=@Fp$J%?%9%/3d$jEvFr2DG=K7!"$+$D!"F0E*Ii2YJ,;6$N%*!<%P!<%X%C%I$NDc8:9k<jK!$rDs0F$9$k!#$3$1$Khj!"hjB?$/$N4D6-$H%"%W%j%1!<%7%g%s$KBP1~9k3H$,2DG=$HJk!#

0J2<!"Bh2>OGO!"=>Mh$NF0E*Ii2YJ,;6J}<0$r4^a?*hetero-TINPAR* $N35MW$K$D$$$F=RYk!#Bh3>OGOK\8&5f$GDs0F$9$kF0E*Ii2YJ,;6J}<0$K$D$$$F=RYk!#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$NO[$J$k%W%m%;%C%5$K!"$=$N=hM}G=NO$K1~$8$?NL$NIi2Y$rJ,;6$5$;$k3HKh$CF9bB.<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*$JJ,3dKh$k%G!<%?$N3djIU1OG$-$J$$!#H3m,$3$1iNJ,3d0J30NG0U$NJ,3d$r9TC?>l9g$O!"%G!<%?$r=jM-9k%W%m%;%C%5$NH=Dj<0$,C1=c$J<0$KOJi:!"<B9T;~$N%*!<%P!<%X%C%I$,Bg$-$/Jk!#

$=$3$G*hetero-TINPAR* GO!"6Q<A4D6-$N;~$N5,B'E*$J%G!<%?J,3d$Khk%G!<%?$N=jM-<TH=Dj$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$$MWA(%W%m%;%C%5$G9=@.$5$1$?2>A[E*$JBNs7W;;5!$rA[Dj$7!"$=$NMWA(%W%m%;%C%5$rCj>]%W%m%;%C%5$H8F$V!#%G!<%?$O!"3FCj>]%W%m%;%C%5$K6QEy$KJ,3d$5$1$k!#Cj>]%W%m%;%C%5$N?t$O!"%f!<%6!<$,%=!<%9%W%m%0%i%`$NCf$G%G%#%1%/%F%#%V$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,$5$1$k!#

hetero-TINPAR GO!"<B9TJ8$N%9%1%8%e!<%j%s%0J}<0$H7F!"J,3d$5$1$?G[Ns%G!<%?$r=jM-9k%W%m%;%C%5$,$=$N%G!<%?$KBP9k%"%/%;%9$r9T$&J8$r<B9T$9$kOwner Computs Rule $r:NMQ$7$F$$$k[y]!#

%G!<%?$O3FCj>]%W%m%;%C%5$K6QEy$KJ,;6$5$1$F$*$j!"$^$?!"3F%G!<%?KBP9$k=hM}$O6Q<AJbNH2>Dj9k$?$a!"3FCj>]%W%m%;%C%5$NIi;;=hM}NL$b6Q<AHJk3H,4|BTG-$k!#

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$9$k!#

(2) <B%W%m%;%C%5$N=hM}G=NO$KH\fN<7?8D?t$NCj>]%W%m%;%C%5$r=$N<B%W%m%;%C%5$KG[J,9k!#

(3) 6cBNE*$K!"$I$NCj>]%W%m%;%C%5$rIN<B%W%m%;%C%5$K3d$jIU1k$+7hDj$9$k!#

(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!#

(2) $H(3) $G!"K\8&5f$NBP>]G"$kF0E*Ii2YJ,;65!G=$rDs6!9k!#$3$1iK4X7F$OBh2.2 @a$G=RYk!#

3F<B%W%m%;%C%5$O!"<+J,$KG[J,$5$1$?3FCj>]%W%m%;%C%5$K6Q<AG[J,$5$1$?%?%9%/$r=hM}9k!#$?$@$7!"3F<B%W%m%;%C%5$G$O%9%1%C%I$r1D@$15/F0$7!"$=$N%9%1%C%IFb$GJ#?t$NCj>]%W%m%;%C%5KBP9$k=hM}$r9T$&!#

3FCj>]%W%m%;%C%5$,<B9T$9Y-%?%9%/$O!"3FCj>]%W%m%;%C%5Kh$KG[Ns$N;2>HHCOO$NO[Jk%k!<%WHJ$k!#1$D$N<B%W%m%;%C%5Fb$G$O!"$3$1$i$N%k!<%W$O$=$N=i4|CM!"=*N;CM$r<B9T;~$KJQ99$9$k3H$G1$D$N%k!<%W$H9k3H$G!"%?%9%/$,M;9g$5$1k3HKJk!#$=$N>\$7$$=hM}J}<0$O1) $r;2>H$5$1$?$$!#

2.2 F0E*Ii2YJ,;65!G=

Hs6Q<A4D6-K*$$$F!"9bB.$KJBNs<B9T$9k?aK$O!"3F7W;;5!$KBP7F!"$=$N=hM}G=NO$K1~$8$?E,@Z$J%?%9%/$r3d$j?6kI,MW,$"$k!#vA0$K:GE,$J3F7W;;5!$N=hM}G=NOHf$rM?$($i1J$$>l9g!"$3$1$r<+F0E*$K5a$a!"$=1K=>CFIi2YJ,;6$r9T$&I,MW$,$"$k!#$^$?!"3F7W;;5!$N=hM}G=NO$,F0E*$KJQ2=9k>l9g!"$3$1$NJQ2=$KBP1~9k$?$a$K!"F0E*Ii2YJ,;6$r9T$$!";~4V$H6&$KJQF0$9$k7W;;5!$NG=NO$KBP7F:GE,$J7W;;NL$N3djEvFr9kI,MW,$"$k!#

$3$1ir<B8=9k$?$a$K!"<B9T;~$K7W;;5!$NIi2Y$r<BB,$7!"$=1rbH$KE,@Z$J%?%9%/J,;6Hf$r5a$a$k!#5a$ai1$?%?%9%/J,;6Hf$K1~8F!"<B9T;~$K3F<B%W%m%;%C%5$X$N%?%9%/$N3dEvFrJQ99$9$k!"F0E*Ii2YJ,;65!G=$,I,MW$HJk!#

$^$?!"*hetero-TINPAR* $O!"Owner Computes Rule $r:NMQ$7$F$$$k$?$a!"Cj>]%W%m%;%C%5$N:FG[J,$O<B:]KO!"$=$N%W%m%;%C%5$K3d$jEvFi1F$$$k%?%9%/$H%G!<%?$NE>AwKhCF9TJo1k!#0J2<!"C1$KCj>]%W%m%;%C%5$NO\F0HO!"Cj>]%W%m%;%C%5$K3d$jEvFi1F$$$k%?%9%/$H%G!<%?$r0\F0$5$;k3HrI=o9bNH9$k!#

hetero-TINPAR GO!"7W;;$K22C$7$F$$$kA4%W%m%;%C%5$,!"$"kDjai1$?;~~E@$G!"6(D4$7$FIi2YJ,;6$r9T$&&D4Jb6(D47?$NIi2YJ,;6@cN,$r:NMQ7F$$$k!#

:FJ,;6$O!"Cj>]%W%m%;%C%5$K3djEvFi1$?%?%9%/

---

[y] BeF~J8$O86B'$H7F:8JU$N%G!<%?$r=jM-9k%W%m%;%C%5$,<B9T$9$k!#

$N:G30%k!<%W$N1 %$%?%l!<%7%g%s$KBP1~9k<B%W%m%;%C%5$N=hM}$,=*oC$?;~E@$G9TJ&bNH9$k!#$3lr%A%'%C%/%]%$%s%H$H8F$V!#%A%'%C%/%]%$%s%HGO!"A4<B%W%m%;%C%5$,JBNs=hM}$r0l;~Dd;_7FF14|rHk3H,2DG=G"$k!#

%A%'%C%/%]%$%s%H$G$O!"0l$DA0$N%A%'%C%/%]%$%s%H$GG[J,$5l?Cj>]%W%m%;%C%5?t$H!"$=$N%A%'%C%/%]%$%s%H$+$i$N7W;;;~4V$rIi2Y>pJsH7$FMxMQ$7!":FJ,;6$,I,MW$HH=Dj9l$P:FJ,;6$r9T$J$$!"$=$&GJ1l$P:FJ,;6$r9TJo$:$K%A%'%C%/%]%$%s%H0J9_$N<B9Tr=N^$^7QB3$9$k!#

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

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

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

(1) Cj>]%W%m%;%C%5$N3dEvJ}<0$K!"C1=c$JO"B33dEv$N$_$,2DG=G"$k!#$3N?$a!"7W;;5!$NG[CVKh$kF0E*Ii2YJ,;6$KMW9k;~4VXN1F6A$,Bg$-$$!#

(2) A4FN<B%W%m%;%C%5$KCj>]%W%m%;%C%5$r>/J/Hb1 DOG[J,7J1lPJiJ$$!#3N$?$a!"Hs>o$K=hM}G=NO$ND$$$<B%W%m%;%C%5$,B8:_$7$?>l9g!"$=$N<B%W%m%;%C%5$NCj>]%W%m%;%C%51 $DJ,$N=hM}N?aK!"A4BN$N<B9T;~4V$,A}Bg9k!#

(3) :FJ,;6N?aNIi2Y>pJs<}=8N?aK!"<B:]KO:FJ,;6$r9T$oJ/Fb!"Bg$-$J%*!<%P!<%X%C%I$rH<$&A4<B%W%m%;%C%5$NF14|$,I,MWHJ$k!#

$=$3$G!"Bh3.1 @a$G!"1 HV$NLdBjE@$KBP7F!"?7$?$K:G>.0\F0%3%9%HJ}<0Kh$kBP=h$rDs0F9k!#Bh3.2 @a$G2 HV$NLdBjE@KBP7$F!"B>$K9bIi2Y$N%f!<%6!<%W%m%;%9$,B8:_9kJI$NM}M3$KhC$F!"=hM}$NNO$,Dc$/JC$F$$$k<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,7J$$$3HKhkBP=h$rDs0F$9$k!#Bh3.3 @a$G3 HV$NLdBjE@$KBP7F!"<+N'Ii2YH=CG<jK!Kh$kBP=h$rDs0F9k!#

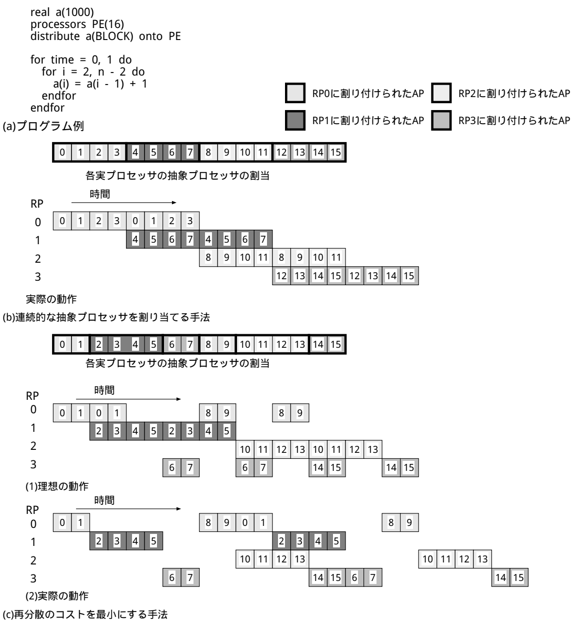
3. F0E*Ii2YJ,;65!G=$N2~NI

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!#)



```
real  a(1000)
processors  PE(16)
distribute  a(BLOCK)  onto  PE

for  time  =  0,  1  do
   for  i  =  2,  n  -  2  do
      a(i)  =  a(i  -  1)  +  1
   endfor
endfor
```

?^1 %W%m%0%i%`$K%k!<%W1?HB0MB8$,$"$k>l9g

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:$7$F:FJ,;6$N;~$NDL?.%3%9%H$r:G>.$KM^$($k<jK!(:G>.0\F0%3%9%HJ}<0) $,9M$(il$k!#

$3$3$G!"SOR JI$N%W%m%0%i%`GO!"Cj>]%W%m%;%C%5?t$N3djEvF$,O"B3$7$F$$$J1l$P%Q%$%W%i%$%s$,Mp$l!"@-G=Dc2<$,5/3k!#$=$3$G!"$3Nh$&$J>l9gKOO"B33dEvJ}<0$r:NMQ$7!"$=$N$[$+$N>l9g$O!":FJ,;6;~$N%*!<%P!<%X%C%I$,>.5/Jkh&$K!":G>.0\F0%3%9%HJ}<0$r:NMQ9k!#8=:_NH3m!"%Q%$%W%i%$%s<B9T$,9T$Jolk+I&$+$O!"%k!<%W1?HB0MB8$,B8:_$7!"$+$D!"$=$N30B&Kb$&1CJ%k!<%W$,B8:_9k>l9gH7$F$$$k!#

:G>.0\F0%3%9%HJ}<0rHC?$?$a$K!"%Q%$%W%i%$%s$,MplkLdBj$D$$$F$O<!@a$G>\$7$/=R$Y$k!#

3.1.2 :G>.0\F0%3%9%HJ}<0$NLdBjE@

SOR Nh$&$K!"%Q%$%W%i%$%s<B9TKh$jJBNs@-$,Cj=P5l$F$$$k>l9g!":G>.0\F0%3%9%HJ}<0GO!"$=$N%W%m%0%i%`$NJBNs@-$,H/4x$5$l$J$$!#?^1 $O!"?^1(a)$N%W%m%0%i%`$N<B9TNc$r<(7F$$$k!#?^1(b), (c) $=$l$>$lO"B33dEvJ}<0!":G>.0\F0%3%9%HJ}<0$r:NMQ$7$?>l9g$N<B9TNcG"$k!#

?^1(b) $NO"B33dEvJ}<0$G$O!"Cj>]%W%m%;%C%5$O$=$l$>$l4 D:$D=gHV$K<B%W%m%;%C%5$K3d$jEvFilF$$$C$F$$$k!#<B:]$N<B9T$G$O!"$^$:!"<B%W%m%;%C%50 $,Cj>]%W%m%;%C%50 $+$i3 $N1 2sL\$NH?I|$r=hM}$7$?8e!"%G!<%?$r<B%W%m%;%C%51 $KE>Aw$9$k!#$=$N8e!"<B

%W%m%;%C%50$O!"2 2sL\$NH?I|$N<B9T$r3+;O$7!"<B%W%m%;%C%51$O!"Cj>]%W%m%;%C%54$+$i7$N1 2sL\$NH?I|$N<B9T$r3+;O9k!#0J2<=g<!!"%Q%$%W%i%$%sJ}<0$G<B9T$,?J$`!#

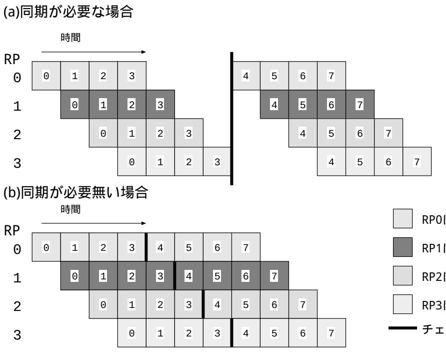
?^1(c)$N:G>.0\F0%3%9%HJ}<0$NNcGO!"Cj>]%W%m%;%C%50,1,8,9$O<B%W%m%;%C%50$K!"Cj>]%W%m%;%C%52$+$i5$O<B%W%m%;%C%51$K!"Cj>]%W%m%;%C%510$+$i13$O<B%W%m%;%C%52$K!"Cj>]%W%m%;%C%56,7,14,15$O<B%W%m%;%C%53$K3djEvFil$F$$$k!#?^1(c)(1)$O!"$=$NM}A[E*$J<B9T$NMM;R$r?^<(7?bNG"$k!#<B%W%m%;%C%50$O!"$^$:Cj>]%W%m%;%C%50,1$N1 2sL\$NH?I|$N=hM}$r7?8e!"<B%W%m%;%C%51$K%G!<%?$rE>Aw9k!#$=$N8e!"<B%W%m%;%C%50$,Cj>]%W%m%;%C%58,9$N1 2sL\$NH?I|$N=hM}$r9kKO!"<B%W%m%;%C%53$+$i%G!<%?$r<u?.$9kI,MW,$"$k!#3N<u?.NBTA;~4V$K!"Cj>]%W%m%;%C%50,1$N2 2sL\$NH?I|$N=hM}$r@h$K<B9T$9k3HKhj9bB.<B9T7F$$$k!#

7+$7!"Bh2.2@a$G=RY?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$$!#7?$,$C$F!"$3$N@)Ls$N$?$a$K!"<B:]$NF0:n$O!"?^1(c)(2)$Nh&KD$^$j!"Cj>]%W%m%;%C%50,1,8,9$,F1$8<B%W%m%;%C%5$K3d$jEvFilF$$$k>l9g!"Cj>]%W%m%;%C%50,1$N2 2sL\$NH?I|$N=hM}$HCj>]%W%m%;%C%58,9$N1 2sL\$NH?I|$N=hM}$O!"K\Mh$O$IAi$+$iGb<B9TG-kK$b4X$oi:!"3N@)LsKhCF8e<T$r@h$K7W;;7J1lPJiJ$$!#$=$N$?$a!"JBNs@-$,H/4x$5l:!"<B9T;~4V$OBgI}$KA}2C9k!#

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

=>Mh$N*hetero-TINPAR*$G$O!"3F<B%W%m%;%C%5$KBP$7>/$J$/$H$b0l$D$OCj>]%W%m%;%C%5$rG[J,9kI,MW$,$"C?$,!"Cj>]%W%m%;%C%5$,G[J,5l$k?t$,%f!<%6!<$,;XDj$7$?ogCM$h$j>/$J$$>l9g$O!"$=$N<B%W%m%;%C%5$KCj>]%W%m%;%C%5$rG[J,$7$J$$$h$&$K7?!#

=hM}G=NO$NDc$$7W;;5!$d!"B>$N%f!<%6!<%W%m%;%9KhCF9bIi2YKJCF$$$k7W;;5!$,4^$^lF$$$k>l9g!"$=$N7W;;5!$KCj>]%W%m%;%C%5$rG[J,9khj$b!"G[J,$;$:$KDL?.$N%*!<%P!<%X%C%I$r8:i7$?J}$,!"<B:]$N7W;;;~4V$OC;$/$Jk3H,$"$k!#$^$?!"<B%W%m%;%C%5$N=hM}G=NOHf$,6KaFBg$-$/Jk$H!"Cj>]%W%m%;%C%5$NN3EY$O8GDj$5lF$$$k$?$a!"$=$NN3EY$,==J,:Y$+$/$J$$>l9g!"Cj>]%W%m%;%C%5$NG[J,Hf$,<B%W%m%;%C%5$N=hM}G=NOHf$KBP1~G-$J$$>l9g$,5/$3$jF@$k!#3Nh&$J>l9g!"=hM}G=NO$NDc$$<B%W%m%;%C%5$K3d$jEvFil?Cj>]%W%m%;%C%5$N=hM}$K;~4VrMW9k?$a!"A4BN$N=hM}$,CY$/Jk3H$,$"$k!#$3Nh$&$J>l9g$O!"Ds6!2DG=$J=hM}G=NO$NDc$$<B%W%m%;%C%5KO!"Cj>]%W%m%;%C%5$rG[J,$7$J$$J}$,NI$$!#



?^**2** F14|$,I,MW$J>l9g$HITMW$J>l9g

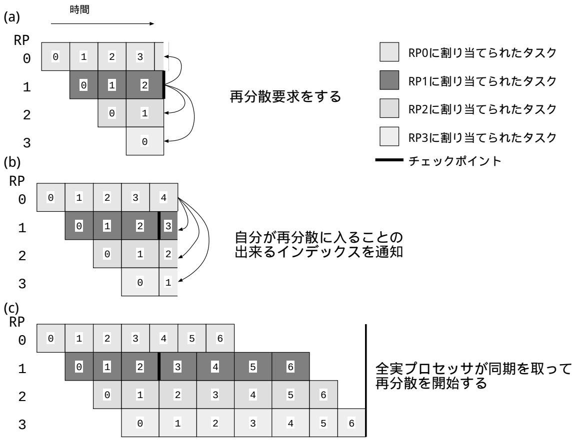
3.3 <+N'Ii2YH=CGJ}<0

hetero-TINPARGO!"":FJ,;6r9k+I&$+$rH=CG9k$@$1$G!"A4<B%W%m%;%C%5$N4V$GF14|$r<hkI,MW,$"$C$?$,!"8=:_$NCj>]%W%m%;%C%5$NG[J,Hf$,:GE,$G$"$k$+$I$&$+$NH=CG4p=`$r!"3F%A%'%C%/%]%$%s%H$K$*$$$FA02s$N%A%'%C%/%]%$%s%H$+$i$N7W;;;~4V$r7WB,$7!"$=$N;~4V$,JQ2=7F$$$k$+$I$&$+H9k3HKhj!"F14|$r<h$i$:$K:FJ,;6$9$kY-$+$I$&$+$NH=CG$r2DG=K7$?!#$3lKhj!":FJ,;6$NI,MW@-$NH=CG$N%*!<%P!<%X%C%I$,BgI}$K8:>/$7$?!#

%W%m%0%i%`$N<B9T$NESCf$GA4BN$GF14|$r<h$k$H!"%Q%$%W%i%$%s7?$NJBNs<B9T$r$9$k%"%k%4%j%:%`$r:NMQ$7$F$$$k%"%W%j%1!<%7%g%s$N>l9g$K$O!"%*!<%P!<%X%C%I$,Bg$-$$!#?^2(a)$K!"$3Nh$&$J%W%m%0%i%`$N<B9TCf$KF14|$r<h$C$?>l9g$N<B9T$NMM;R$r<($9!#$3$N?^$N%W%m%0%i%`$O!"$"$k<B%W%m%;%C%5$,$"$k%V%m%C%/$r=hM}$9kK$O!"1$DA0$NHV9f$N<B%W%m%;%C%5$,F1$8HV9f$N%V%m%C%/$N=hM}$r=*$($F$$$kI,MW$,$"$k!#%Q%$%W%i%$%s7?$NJBNs<B9Tr9$k%"%k%4%j%:%`$r:NMQ$7$F$$$k%"%k%4%j%:%`$G$O!"<B9T3+;O$+$i<B:]$KJBNs$F0: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!#

$3$3$G!"0lC6!"F0E*Ii2YJ,;6$,9Tol$?$"HG$O!"7W;;;~4V$,JQ2=7F$$$J$$4V$O!"Cj>]%W%m%;%C%5$NG[J,Hf$O:GE,$G$"$k$,!"7W;;;~4V$NJQ2=$,8!=P$5l?H-$K!"8=:_$NCj>]%W%m%;%C%5$NG[J,Hf$,:GE,GJ$/$JC?$HH=Dj2DG=$G$"$k!#$=$3$G!"3F%A%'%C%/%]%$%s%HK*$$$F!"A02s$N%A%'%C%/%]%$%s%H$+$i$N7W;;;~4V$r7WB,$7!"$=$N;~4V$,JQ2=7F$$$k$+H]$+$GIi2Y$N:FJ,;6$,I,MW$G$"$k$+$I$&$+$rH=CG$9kh$&$K2~NI$r9T$JC?!#

$"$k<B%W%m%;%C%5$,:FJ,;6$,I,MWG"kHH=CG7?H-$O!"$=lrA4BN$KDILN$9$k!#$3$N;~$K!"<+J,$,:FJ,;62DG=$J;~E@$r;XDj$9$k!#$3$NDILN$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$KDILN$9$k!#3F<B%W%m%;%C%5$O!"<u



?^**3** :FJ,;6$NI,MW@-$NHsF14 |H=CG

$1<h$C$?:FJ,;62DG=$J;~E@NCfG!"0lHV!"=hM}$N?J$s$G$$$kH3m^$G!"=hM}$r?J$a!#$=3G!"A4%W%m%;%C%5$GF14 |$r<hCF:FJ,;6$r3+;O$9$k!#

3N<jK!Kh$j!":FJ,;6$NI,MW@-$NH=CG$N%*!<%P!<%X%C%I$,6K$a$F>.$5$/$J$k!#?^2(b)$K!"%Q%$%W%i%$%s7?$NJBNs<B9T$r9k%W%m%0%i%‘$,:FJ,;6$r9TJ&>l9g$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;XDj$5l?IQEY$GH=CG$r9k3HKhCFH=CG$N2s?t$r8:i7$F$$$?$,!"Kh2sH=CG$r9k3H$,2DG=$KJC$?!#$3lKhj!"Ii2Y$NJQ2=$KIR46$KH?1~$7$F:FJ,;6$r9k3H$,2DG=$KJk!#

4. @-G=I>2A

K\>OGO!"F0E*Ii2YJ,;65!G=$N2~NI$KhC$FF@$il?9bB.2=$NI>2A$r9TJ&!#

4.1 I>2A4D6-

I>2AKO!"SOR K!$HRed-Black SOR(0J2<!"RB-SOR)K!$N2$D$N%W%m%0%i%‘$rMQ$$$?!#;HMQ7?9TNs%5%$%:$O1024×1024G"$k!#FC$K$?$@$7=q$-NJ$$>l9g$O!"Cj>]%W%m%;%C%5$N8D?t$O128 8D$H7?!#

%W%m%0%i%‘$N<B9T$O!"10Mbps$N%$!<%5%M%C%H%9%$%C%A$Khj@\B3$5$l$?SPARCstation 20(0J2<SS20)4 Bf!"SPARC Ultra-1(0J2<Ultra)4 Bf$HSPARC Classic1 Bf(0J2<Classic)Kh$j9=@.$5l?4D6-K*$$$F:GBg4 Bf9=@.$G9T$$!"86B’E*$K!"B>$N%f!<%6!<%W%m%;%9$NL5$$L5Ii2Y$N>uBV$GB,Dj$r9T$C$?!#$^$?!"DL?.%i%$%V%i%jH7$FMPI$^{2)}$N<BAu=hM}7O$G$"$kMPICH$^{3)}$r;HMQ7?!#

4.2 Cj>]%W%m%;%C%5$NG[CV$NI>2A

Cj>]%W%m%;%C%5$N3d$jEvFN;~$N!"O"B3Cj>]3dEvJ}<0$H!":G>.0\F0%3%9%HJ}<0N=l>lr:NMQ7?H-$N<B9T;~4V!"7W;;;~4V!"5Z$SDL?.;~4V$rHf3S$7!"N><jK!$NI>2A$r9TC?!#

I=**1** Cj>]%W%m%;%C%5$NG[CV$NI>2A

7W;;5! $N=gHV	;HMQ <jK!	<B9T ;~4V[s]	7W;; ;~4V[s]	DL?. ;~4V[s]	:FJ,;6 ;~4V[s]
SOR					
SUUS	:G>.	280.29	179.16	65.43	37.03
SUUS	O"B3	284.15	183.12	63.94	39.90
UUSS	:G>.	843.56	181.51	596.69	38.85
UUSS	O"B3	360.75	181.41	71.16	109.86
RB-SOR					
SUUS	:G>.	165.12	78.57	34.09	52.44
SUUS	O"B3	165.61	75.83	32.49	57.24
UUSS	:G>.	166.34	80.55	30.78	55.60
UUSS	O"B3	187.03	78.66	27.82	80.66

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

†	‡	:G=* J,;6Hf	<B9T ;~4V[s]	7W;; ;~4V[s]	DL?. ;~4V[s]	:FJ,;6 ;~4V[s]
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

†:Cj>]%W%m%;%C%5?t
‡:Cj>]%W%m%;%C%5$rG[J,$7$J$$$h$&$K9kogCM

I>2A4D6-$O!"SS20 2 Bf$HUltra 2 Bf$rMQ$$!"<B%W%m%;%C%5$NHV9f$rSS20!"Ultra!"Ultra!"SS20$H$$$&=gHV(0J2<SUUS)$G3d$j?6C?>l9g$H!"Ultra!"Ultra!"SS20!"SS20$H$$$&=gHV(0J2<UUSS)$G3d$j?6C?>l9g$N2DL$j$NHs6Q<A4D6-$H7?!#I>2A%W%m%0%i%‘$O!"2000 H?I |$NSOR!"250 H?I |$NRB-SOR$r;HMQ7?!#

I=1$K<B9T;~4V!"5Z$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$r=|$$$?;~4V!":FJ,;60J30$NDL?.$KMW7?;~4V!":FJ,;6;~$NDL?.$KMW7?;~4VG"$k!#

SORGO%Q%$%W%i%$%s<B9TrMp5$J$$O"B33dEvJ}<0$NJ}$,:FJ,;60J30$NDL?.;~4V$,8:>/9k!#3l$O!"DL?.;~4V$NCfKO!"%Q%$%W%i%$%sNMpl$KH<$C$FA}Bg$9$k<u?.BT$A;~4V$b4^$^lk$?$aG"$k!#RB-SOR$Nh&$K%k!<%W1?HB0MB8$,J1lP!":G>.0\F0%3%9%HJ}<0$NJ}$,!":FJ,;6;~$NDL?.NL$N8:>/Kh$k<B9T;~4VA4BN$N8:>/$,F@$ilk!#

RB-SOR$rUUSS$NG[CV$G<B9T$7$?>l9g$K!":G>.0\F0%3%9%HJ}<0$r:NMQ$7$?8z2L$,:GbBg-$/8=$l!"Ls10%<B9T;~4V$,8:>/$7$F$$$k!#

4.3 Cj>]%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=@.$G

I=**3** :FJ,;6$N4V3V$KhkJQ2=

:FJ,;6$N 4V3V	<B9T ;~4V[s]	7W;; ;~4V[s]	DL?. ;~4V[s]	:FJ,;6 ;~4V[s]
:FJ,;6$N%A%'%C%/;~$KF14 |rH$k>l9g!'				
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
:FJ,;6$N%A%'%C%/;~$KF14 |Hi$J$$>l9g!'				
1	97.68	44.45	17.10	35.97

I>2A$r9T$C$?!#I>2A%W%m%0%i%`$O!"H?I|2s?t$O500 2s$NSOR $rMxMQ$7!"Cj>]%W%m%;%C%5?t$r128!"64!"32!"16 HJQ($FI>2A$r9TC?!#A4BN$NCj>]%W%m%;%C%5$,128 8D$+64 8D$N>l9g$O!"Cj>]%W%m%;%C%5$,G[J,?t$,2 $D0J2<$N>l9g!"A4BN$NCj>]%W%m%;%C%5$,32 8D$+16 8D$N>l9g$O!"Cj>]%W%m%;%C%5$,G[J,?t$,1 DN>l9g$O!"A4$/G[J,7J$$$H7?!#

I=2 $K<B9T7k2L$r<($9!#Classic KO!"Cj>]%W%m%;%C%5$rG[J,$7$J$$$H!"Cj>]%W%m%;%C%5?t$,!"32 8D$+16 8D$N>l9g$O<B9T;~4V$,C;$/JC$F$$$k!#:GBg$G!"Cj>]%W%m%;%C%5?t$,16 8DNH$-$KLs15%$N@-G=8~>e$,F@il$k!#0lJ}!"Cj>]%W%m%;%C%5$,64 8D0J>e$N;~$O!"A4BN$N<B9T;~4V$,3%$[$IA}Bg7F$$$k!#

3l$O!"Cj>]%W%m%;%C%5?t$,>/$J$$$J}$,Ii2YJ,;6$NN3EY$,Bg$-$/$J$j!"7W;;G=NO$N9b$$<B%W%m%;%C%5$HDc$$%W%m%;%C%5$N@-G=Hf$K$"$o$;$?Ii2YJ,;6$,$G$-$J$/$JCF$$$k$?$aG"$k!#

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

<+N'Ii2YH=CGJ}<0Kh$kF14|$r<h$k2s?t$N8:>/Kh$k%*!<%P!<%X%C%I$NDc2<$rI>2A$9$k!#I>2A$K$O!"Ultra $r2 Bf$HSS20 $r2 Bf$r!"Ultra!"SS20!"SS20!"Ultra $H$$$&=gHV$GG[CV$7$?4D6-$GSOR $r<B9T$7$F9T$JC?!#

4.4.1 Ii2Y$,F0E*$KJQ2=7J$$>l9g

:FJ,;6$NI,MW@-$NH=CGN?aKF14|rHC?H-$N%*!<%P!<%X%C%I$r8+k?aK!"F14|rI,MWH9k>l9g$N%A%'%C%/$NIQEY$rJQ2=$5$;$?!#

I=3 $KI>2A$N7k2L$r<($9!#F14|rI,MWH9k=>Mh$N<jK!$N>l9g!"Kh2s%A%'%C%/r9kH!"50 2s$K1 2s9T$&>l9gKHfY$F!"<B9T;~4V$,40%$bA}2C$7$F$$$k!#HsF14|Kh$kH=CG$N>l9g$O!"Kh2s%A%'%C%/$r9TCF$b50 2s$K1 2sF14|$r<h$C$F%A%'%C%/$r9T$&>l9g$KHfYF!"<B9T;~4VOo$:$+G"k,C;=L5l$F$$$k!#3lKh$j!"HsF14|H=CG$N>l9g$NH=CG$N$?$a$N%*!<%P!<%X%C%I$O==J,$K>.$5$$$3H,<(5l$?!#

4.4.2 Ii2Y$,F0E*$KJQ2=9k>l9g

SOR $N%W%m%0%i%`(%?%9%/1) $N<B9T3+;O$N52 IC8e$K!"2 Bf$NSS20 $N$&$A$N1 $D$K30E*Ii2Y$H$7$FC`<!4D6-MQ$NSOR $N%W%m%0%i%`(%?%9%/2) $b<B9T$7$?!#

I=4 $K<B9T7k2L$r<($9!#=>Mh$N<jK!GO!"59.03 IC$N;~E@$G:FJ,;6$r3+;O$7$F$$$k!#$=$lKBP7$F!"HsF14|H=CG$N<jK!GO!"53.38 IC$N;~E@$G:FJ,;6$r3+;O$7$F$$$k!#%?%9%/2 $N<B9T$KhkIi2Y$NJQ2=$O!"52 IC8e$KH/@8$9kN$G!"2~NI8e$N<jK!GO!"Ii2Y$,JQ2=$9kH$9$0K=lr46CN7FF0E*:FJ,;6$,<B9T$5lF$$$k!#

I=**4** F0E*:FJ,;6Kh$kIi2YJ,;6$NI>2A

:G=* J,;6Hf	%?%9%/2 $NEjF~$K H?1~7F:FJ,;6$r 3+;O$7$?;~4V(s)	%?%9%/1 $N <B9T;~4V(s)	%?%9%/2 $N <B9T;~4V(s)
:FJ,;6$N%A%'%C%/;~$KF14 |rH$k>l9g!'			
48:18:15:47	59.03	141.54	377.36
:FJ,;6$N%A%'%C%/;~$KF14 |rHiJ$$>l9g!'			
49:19:12:48	53.33	130.82	342.78

$=$N$?$a!"%?%9%/1!"%?%9%/2 $N<B9T;~4V$O!"=>Mh$N<jK!$G$O!"$=l>$l141.54 IC$H377.36 ICG"C?N,!"<+N'Ii2YH=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!#

5. $*$ojK

K\9FGO!"Hs6Q<A4D6-$rBP>]$H7?JBNs%3!<%I@8@.$r9T$&JBNs2=%3%s%Q%$%i*hetero-TINPAR* $NF0E*Ii2YJ,;65!G=$N2~NIKD$$$F=RY?!#Cj>]%W%m%;%C%5$N3dEvJ}<0$r3F%"%W%j%1!<%7%g%s$H!"3F%W%m%;%C%5$N@-G=$K1~$8$F=@Fp$KJQ2=G-kh$&$K7?!#$^$?!":FJ,;6r9k+I&$+$NH=CG$r!"F14|$r<hiJ$/$H$b2DG=$H7?3HKhCF!"F0E*$KJQ2=$9$k7W;;5!4D6-$KBP7F>/$J$$%*!<%P!<%X%C%I$GBP1~$G$-$kh&KJC?!#

@-G=I>2AKh$j!"B?MM$J%"%W%j%1!<%7%g%s$KBP1~$G$-$kh&KJC?3H$G!"2~NIA0$HHf3S7F:GBg10%$N<B9T;~4V$NC;=L$r?^$k3H$,$G$-$?!#=hM}G=NO$NDc$$<B%W%m%;%C%5$K!"Cj>]%W%m%;%C%5$r3djEvF$J$$$3HKhC$F:GBg15%$N@-G=8~>e$,F@$il?!#$^$?!"F0E*$KJQ2=$9$k7W;;5!4D6-$KBP7F?WB.$KBP1~$G$-$kh&KJC?3H$G!"<+$i$H!"B>$N%f!<%6!<%W%m%;%9$NN>J}$,,10%DxEY$N@-G=8~>e$,F@il$?!#

<U<- K\8&5f$N0lIt$O!"J8It>J2J3X8&5fHqJd=u6bFCJL8&5f0w>)NeHq2]BjHV9f00093007 Kh$k!#

;2 9M J8 8%

1) 8eF#?5LiB>!'JBNs2=%3%s%Q%$%iTINPAR Kh$kHs6Q<A7W;;5!4D6-8~$1%3!<%I@8@.<jK!, JSPP'97, pp.205–212,1997.
2) Message Passing Interface Forum: MPI: Message-Passing Interface Standard,1995.
3) Bridges,P. et.al: Users' Guide to MPICH, a Portable Implementation of MPI, Argonne National Laboratory.