HFMQD6JBNs OS *SSS–CORE* $N ;q8;%9%1%8%e!<%j%s%0J}<0$NI>2A

?.9q M[Fs0:† >>K\ >0†† J?LZ 7I††
Yojiro Nobukuni Takashi Matsumoto Kei Hiraki

†!J3t!K%"!<%D%F%C%/ Arts Teck Inc.
††El5~Bg3XM}3X7O8&5f2J University of Tokyo

35 MW

NUMA 4D6-$GJBNs%W%m%;%9$N8zN(E*$J<B9T$rK8$2$k3HJ/%^%k%A%f!<%6!?%^%k%A%8%g%V4D6-$r9=C[$9kK$O!"%a%b%j%Z!<%8$JIN<B;q8;$N;HMQ>u67$r9MN8$7$?%9%1%8%e!<%j%s%0$r9T$J$$!"%7%9%F%`A4BN$N@-G=$r$"$2$k$3$H$,M-8z$G$"$k!#K\9F$G$O>\:Y3NN(%b%G%k>e$G!"6qBNE*$J%a%b%j4IM}J}<0!?%"%/%;%9IQEY!?%"%/%;%9%3%9%H$rIU2C$7$?%7%_%e%l!<%7%g%s$K$h$j!"JBNs%W%m%;%9Kh$K=jM-$9$k<B%Z!<%8>pJs$rMxMQ$7$?%9%1%8%e!<%j%s%0J}<0!"$*$h$S%Z!<%8$NJ,N`$K4p$E$$$?%a%b%jCV49J}<0$NI>2A$9$k!#

1 O8aK

NUMA 7?%7%9%F%`$O!"0B2A$J9=@.MWAG$rB??t7k$SIU$1$F$g5,LO$J%7%9%F%`$r9=C[$7!"9b$$=hM}G=NO$rF@$k3H$,$G$-$kFC'D'$r;}$D!#6aG/$N%M%C%H%o!<%/<~JU$N@-G=8~>e$rGX7J$K!"JBNs%"%W%j%1!<%7%g%sN?aN<B9T;Y1g5!9= [6]!"JBNs4D6-2<GN3F<o:GE,2=5;K!$N8&5f!?3+H/ [9] [8]$Khj NUMA 7?JBNs7W;;5!>eGN9b8zN($GHFMQ@-$r;}C?<B9T7ABV$,2DG=$HJCF-$?$!7+7J$,$i!"HFMQ$J%^%k%A%8%g%V!?%^%k%A%W%m%;%9;HMQ7ABVK*$$$F9b8zN($J<B9T$r<B8=9k$?$aKO!"8D!9$N%W%m%;%9$K$*$1$k8zN(2=!?:GE,2=5;K!$@1GJ/!"%*%Z%l!<%F%#%s%0%7%9%F%`%l%Y%kKh$k%8%g%V!?%W%m%;%9$r8YC?9b8zN(2=$,IT2D7g$G$"$k!#

;~J,3d$rMxMQ$7$?JBNs4D6-8~$1$N%9%1%8%e!<%j%s%0J}<0$H7F$O!" gang scheduling $NM%0L@-$,Js9p5l$F$$$k [1]!#JBNs%W%m%;%9C1BN$N<B9T@-G=$r9MN8$7$?>l9gKb!"F14|BTAr6KNO8:i9$3$H$,2DG=$J gang scheduling $OM-8z$G$"$k!#;q8;>pJs$rMxMQ$7$J$$ matrix algorithms [5] $O!"%W%m%0%i%`<B9TC10L$N%W%m%;%C%5XN%^%C%T%s%0K*1k%R%e!<%j%9%F%#%C%/%9KMjk!#$=$N$?$a;q8;$N@jM->u67$rL5;k7?%^%$%0%l!<%7%g%s$d!" processor fragmentation $,LdBj$HJk!#%a%b%jXN%"%/%;%9%3%9%H$,5wN%$KhC$F0[$kJ,;64D6-GO!"%9%1%8%e!<%j%s%0$K<B;q8;$N;HMQ>u67$rH?1G$5$;$k3HKh$j%3%9%H$N9b$$%"%/%;%9$r8:>/$5$;$k9b8zN(2=$,I,?\$G$"$k!#

;q8;>pJs$rMxMQ$9$kJ}<0$K!"=8Cf5-217?JBNs7W;;5!8~1N cache affinity J}<0 [7]$,$"k,!"MFNL$N>.$5$J%-%c%C%7%e$G$O8z2L$,=P$J$$!#Bg5,LOJ,;64D6->eG6(D4$7$?;q8;4IM}$r9T$&KO!"3HD%@-$d4IM}8zN($NE@$+$i3,AX2=5l$?OHAH$,I,MWG"$k!#3,AXE*$J%9%1%8%e!<%j%s%0$r9T$&bN$K DHC [4]$H Intel Paragon [2]$,$"$k!# DHC $O Buddy %7%9%F%`$Khk3,AX2=4IM}$r9T$$!"%i%&%s%I%m%S%s$r4pK\$H7F$*$j!"%W%m%;%9?t$K4p$E$$$?Ii2Y>pJs [3]N_$rMxMQ$9$k!# Paragon GO=@Fp$J%W%m%;%C%5J,3d$,2DG=G"k,!";q8;>pJs$OMxMQ7J$$!#$^$?3F%W%m%;%C%5>eGN%9%1%8%e!<%j%s%0$b%+!<%M%k$,<B9T9k!#

K\9FGO HFMQD6JBNs%*%Z%l!<%F%#%s%0!&%7%9%F%` *SSS–CORE* [10]$K$*$1$k;q8;4IM}5!9=$N35N,=R$Y!"%W%m%;%9$N<B;q8;>pJs$rMxMQ$7$?%9%1%8%e!<%j%s%0J}<0$J$i$S$K!"%a%b%j%Z!<%8$NJ,N`KB'C$?%a%b%jCV49J}<0$N%7%_%e%l!<%7%g%sKh$k8zN(2A$r<($9!#

2 *SSS–CORE* $N;q8;4IM}5!9=

2.1 *SSS–CORE* $N%9%1%8%e!<%j%s%0J}<0

SSS–CORE $O!"%f!<%6!?%+!<%M%k J,N%$N2%l%Y%k%9%1%8%e!<%j%s%0$r:NMQ$9$k!#%+!<%M%k$O3F%W%m%;%9$,Ds<($9$k%9%1%8%e!<%j%s%0@)Ls$K=>CF:GbE,EvJ;q8;$r!"3,AX2=4IM}$5l?;q8;>pJsrbHK%W%m%;%9C10L$K3dEv$F$k!#3,AX;q8;4IM}$r<B8=9k$?$a!" *SSS–CORE* GO2>A[E*$J;q8;4IM}LZ9=B$$rMQ0U9k!#K\9FK*$$$FO3lr;q8;4IM}LZ$H8F$V!#;q8;4IM}LZGOO@M}E*$K3F%N!<%IKh$K!"%N!<%I$r%k!<%H$H9kItJ,LZ$NNN0h$K4^$^$l$k%W%m%;%C%5$H<B%Z!<%8$NAm?t$*hS!"%U%j!<$J%W%m%;%C%5$H<B%Z!<%8$NAm?t!"$JiS$K%W%m%;%9Kh$K ID $*$h$S;HMQ$7$F$$$k%W%m%;%C%5$H<B%Z!<%8$NAm?t$r5-O?$9$k!#$^$?%k!<%H%N!<%I$O3NB>$K!"%W%m%;%9Kh$K%9%1%8%e!<%j%s%0@)Ls!"M%@hEY!"%[!<%`%N!<%I!J8e=R!K$rJ];}$9$k!#

8=:_$NJBNs2=%3%s%Q%$%i$O!";q8;$,C10l%W%m%;%9$K@jM-$5lF$$$k$H2>Dj$7$F$$$k!#2f!9$NL\I8$O$=$Nh&$J3%s%Q%$%i$,EG$/%*%V%8%'%/%H%3!<%I$rHFMQ4D6->e$G<B9T9k3HK"$k!#%^%k%A%f!<%6!?%^%k%A%8%g%VHFMQ4D6-GO!"3F%W%m%;%9$N;q8;$X$NMM!9$JM_5a$rK~$?$9$3HG8zN(2=$,2DG=$HJk!#%9%1%8%e!<%j%s%0@)Ls$O!"%W%m%;%9$,%+!<%M%k$K;q8;$XNM_5arEA$($k$?$a$KMxMQ$5lk!#%9%1%8%e!<%j%s%0@)LsNNcH7FBf?t8GDj@)LsGO!"%W%m%;%9$O%+!<%M%k$KBP7F<+J,$,I,MW$H9kMWAG%W%m%;%C%5?t$r0lDj?t;XDj$9$k!#$^$?2DJQBf?t@)Ls$O>/7:DG

$b%W%m%;%9$K%W%m%;%C%5$r3d$jEvFk3H$,2DG=$HJk!#:#
$N%7%_%e%l!<%7%g%s$G$O%W%m%;%9$NJBNsEY$OJQ2=$7$J$$$N$G
%9%1%8%e!<%j%s%0@)LsH7FOBf?t8GDj@)Ls$rMQ$$$k!#

3 %7%_%e%l!<%7%g%s!&%b%G%k

K\9FGOI>2A$N@:EY8~>e$rL\E*H7F3l^GN8&5f$GMxMQ$7$?%b%G%k [13] [12]$r3HD%$7!" OS %l%Y%k$N%7%_%e%l!<%7%g%sN?aN4JN,2=5l$?>\:Y3NN(%b%G%k$r9=C[7?!#

BP>]H9kN$OJ,;6%a%b%j4D6-$G$"$k!#%a%b%j$H%W%m%;%C%5$NBP$r%/%i%9%?$H$7!"Aj8_7k9gLV$OLZ9=B$$r2>Dj9k!#%M%C%H%o!<%/$OFs=E2=$5l?%9%$%C%A%s%0%M%C%H%o!<%/$G!"%9%$%C%A%s%0%N!<%I$K$*$$$F$a%C%;!<%8$r%P%C%U%!%j%s%0$9$k%o%s%[%C%WDL?.$r9T$J$&!#%N!<%I$O3F=PNOKBP7$F!"%N!<%I$X$NF~NO$rJ,$N%(%s%H%j$r;}$D%P%C%U%!$r;}$D!#%Z!<%80\F0$*hS$=$NB>$NDL?.$NFsDLjK$D$$$F!"%N!<%I4V$N 1 %[%C%W$rDL2a9k$?$a$N4pK\%3%9%H$r%Q%i%a!<%?H7$FM?$($k!#%Z!<%8$N0\F0$*$hS=$NB>$NDL?.KBP7FO$=$l$>$l!"%Z!<%80\F04pK\%3%9%H$*$h$SDL?.4pK\%3%9%H$H3F;^$NBS0hG\N($H$+$i;;=P7?%3%9%H$rIU2C$9$k!#?J9TJ}8~$N%P%C%U%!$*$h$S;^$,6u$$$F$$$J$$>l9gOBT?5l$k!#

%W%m%;%9$OMW5a%W%m%;%C%5Bf?t$HF1?t$N%9%l%C%I$Khj9=@.5l$k!#JBNsEY$O0lDj$G!"@8@.;~$+$i=*N;;~$^$GJQ2=$7$J$$!#0l%/%i%9%?K*1kJBNs%W%m%;%9$N<B9T%3%s%F%-%9%H$r%9%l%C%I$H8F$V!#3F%9%l%C%I$O%W%m%;%9Fb$K6&M-6u4V$H8GM-$NHs6&M-6u4V$r;}$D!#3F%W%m%;%9$NN>6u4V$K$O!"$=l>$lJL!9$N%Z!<%8C10L$N%a%b%j;2>HIQEYI=$rM?$($k!#3F6u4VK*1k;2>HNs$O!";2>HIQEYI=$K$*$1$kAmIQEY$KBP9k3F%Z!<%8$N;2>H?t$rHfH7$F3NN(E*$K@8@.9k!#

6&M-6u4VKBP7FOJ,;66&M-%a%b%j%7%9%F%`$r9=C[$9$k!#0l4S@-4IM}$O sequential consistency %a%b%j%b%G%kKB'C$?%"%C%W%G!<%HJ}<0$G!"=>CF%Z!<%8$OCV49$5lJ$$8B$j%a%b%j$K;D$k!#6&M-%Z!<%8$X$N%"%/%;%9$O%"%/%;%9;~$K%-%e!<$K7R$,$l!"%i%$%H$N>l9gKO%*!<%J!<$+$i$N%"%C%W%G!<%H$NAw?.H=lKBP9k Ack $NJV?.$H$,9T$olk!#$^$?%a%b%j;2>H%3%9%H$O!"%/%i%9%?Fb ≪ %/%i%9%?4V ≪ #2<!5-21$H$$$&2>Dj$rH?1G$9kh$&$K@_Dj9k!#%9%1%8%e!<%j%s%0Kh$j%9%l%C%I$N3djEvF0LCV$,JQ2=$7$?>l9g$K$O!"%m!<%+%k%Z!<%8$O%M%C%H%o!<%/$r2p$7$F on-demand $K0\F0$9$k!#%W%m%;%9$N3djEvFNN0h$,JQ2=$7$?>l9g$K$O!"8=:_$N3djEvFNN0h30$KB8:_$9$k6&M-%Z!<%8$O%3%9%H0$G>C5n$9$k!#

%W%m%;%9$N<B9T$O%/%m%C%/%Y!<%9$N3NN(%b%G%k$G!"F14|BTAKtO%Z!<%8BT$A>uBV$GJ1lP3F%/%m%C%/Kh$K%a%b%j;2>H$r9TJ&!#$^$?%W%m%;%9$N%9%l%C%I$O!"M?$($il?M-8z<B9T%/%m%C%/4V3V$G%i%s%@%`$JAH9g$;$N%9%l%C%I4V$GF14|$r5/$3$9!#F14|$O!"F14|E@$XE~C#$7$?%9%l%C%I$+$i%i%s%@%`$KA*Br5l$?2>HIQ%"$N%k!<%H!&%9%l%C%IXNAw?.$H!"$=lKBP9kJV?.HG<B8=5l$k!#$3$3$GM-8z<B9T (;~4V / %/%m%C%/) HO!"%Z!<%8 /F14|BT$A0J30$NF0:nr7$? (;~4V / %/%m%C%/?t) N3HG$"$k!#

3.1 %9%1%8%e!<%j%s%0J}<0

A05-%7%_%e%l!<%?>e$K#5$D$N%9%1%8%e!<%j%s%0J}<0$r<BAu7?!#3FJ}<06&$K!"%?%$%`%9%i%$%9Kh$K;q8;;HMQ$N%(!<%8%s%0$r9MN8$7$?M%@hEY7W;; [11]$r9T$J$$!"M%@hEY$N9b$$%W%m%;%9$+$i=g$K!"$=l>$l0J2<$K<($9J}K!$G%9%1%8%e!<%j%s%0$r9T$J$&!#

algo0 %i%s%@%`KI,MWJ?t$@$1%/%i%9%?$rA*Br$73djEvF$kJ}<0

algo1 %7%9%F%`Cf$N%/%i%9%?$rC<$+$i=gKI,MWJ$@$13djEvF$kJ}<0

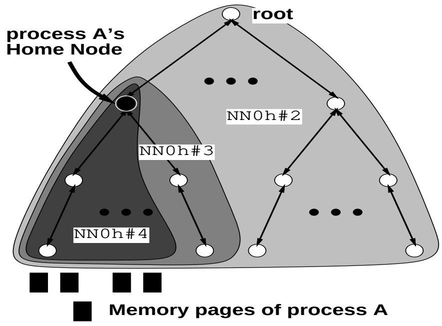
algo2 =iaK%[!<%`%N!<%I0J2<$NNN0h$K3dEv$r;n$_!"<:GT7?>l9gKO%k!<%H%N!<%I0J2<$NNN0h$G!"<+J,$N%Z!<%8$,B8:_9kNN0h$+$i3djEvF$kJ}<0

algo3 %[!<%`%N!<%I0J2<$NNN0h$N$_$G%Z!<%8N"$kNN0h$+$i3d$jEvFkJ}<0

algo4 %[!<%`%N!<%I0J2<$NNN0h$G<+J,$N%Z!<%8$,B8:_9kNN0hN_$r3d$jEvFkJ}<0

$?$@$7>e5-$G%[!<%`%N!<%I$H$O;q8;4IM}LZ>e$N%N!<%I$G!"%W%m%;%9$NMW5aBf?t0J>e$N%W%m%;%C%5$r4^$`ItJ,LZ$KBP1~$9kbNG!":G2<0L%l%Y%k$K0LCV$9kbNN3HG"$k!#$9Jo$A%[!<%`%N!<%I$O!"0l$DA0$N%9%1%8%e!<%j%s%0;~$N3dEvNN0h$rBeI=$7$F$$$k!#?^ 1$K%[!<%`%N!<%I$NNc$r<($9!#?^Cf$G%W%m%;%9 A $N%[!<%`%N!<%I$O!"<+J,$N%Z!<%8$rJ;}9kNN0h 4 $rJq4^$9$kItJ,LZ$N%k!<%HKEv?$k%N!<%I$G$"$k!#

Bf?t8GDj%9%1%8%e!<%j%s%0@)Ls$rMQ$$$F$$$k$?$a!" algo2, 3, 4 GO3djEvFBP>]NN0h$KI,MWBf?t$r3NJ]G-$J$$%W%m%;%9$N%9%1%8%e!<%k$OD|ak!#=iaKI,MWBf?t$N3NJ]$r;n$_$kNN0h$H!"$=lK<:GT7?>l9g$NBP=hK!$,0[JC$F$$$k!# $^$?%W%m%;%9$K



?^ 1 ;q8;4IM}LZ$H%9%1%8%e!<%j%s%0BP>]NN0h

3djEvFil$?%/%i%9%?$X$N%9%l%C%I$N%9%1%8%e!<%j%s%0$O!"0J2<$NDLjG$"$k!#

- A02s$N3dEv$H=EJk%/%i%9%?KOA02s$HF1$8%9%l%C%I$r%9%1%8%e!<%k$9$k
- $=$l0J30$N%/%i%9%?$K$O!";D$j$N%9%l%C%I$r=g$K%9%1%8%e!<%k$9$k

A0@a$G=R$Y$?$h$&$K!"F10l%9%l%C%I$,F10l%/%i%9%?$G<B9T5llP%m!<%+%k6u4V$O:FMxMQ$5lk!#%9%l%C%I$N%9%1%8%e!<%k0LCV$,0\F0$7$?>l9gKO!"%m!<%+%k6u4V$N%Z!<%8$O%/%i%9%?$r1[$($F%M%C%H%o!<%/>e$r0\F0$7$J1lPJiJ$$!#=>CF3djEvFNN0h$,$JkY$/=E$Jkh$&$K7?J}$,!"%m!<%+%k%Z!<%8$N0\F0$,>/$J$$!#

3.2 %Z!<%8CV49J}<0

F14|6&%a%b%j4D6-%7%9%F%`>e$GJ,;66&M-%a%b%j$rA[Dj$9$k$H!"$O!"F14|E@$X$J$&2>HIQEY$*$h$S:F%"%/%;%9;~$N%"%/%;%9%3%9%H$N0c$$$K$h$j%Z!<%8$rJ,N`9k3H$,2DG=$G$"$k!#%Z!<%8$NJ,N`$,G-lPF14|2>HIQEY$,>/$J$/:F%"%/%;%9;~$N%3%9%H$,>.$5$$%Z!<%8$+$iCV49BP>]H9$k8zN(E*$J%Z!<%8CV49J}<0$,2DG=$HJk!#

JBNs%W%m%;%9$N>l9g0lHL$K$O6&M-NN0h$N;2>HN($OHs6&M-NN0h$KHfYF>.$5$$!#:F%"%/%;%9;~$N%3%9%H$K$D$$$F$O!"%M%C%H%o!<%/Fb$X$N%"%/%;%9+!"Fs<!5-21$X$N%"%/%;%9$G$"$k$+$KCFJ,N`$,2DG=$G$"$k!#$5$i$K$=$N%3%9%H:9$O*!<%@!<$H$7$F0c$&$H2>Dj$G$-$k!#$=$3$G!"Av9T$9$k2DG=@-$NDc$$%W%m%;%9$N6&M-%3%T!<%Z!<%8$+$iCV49BP>]$H$9$k$3$H$G!"@-G=8~>e$r$O$+$k$3$H$,2DG=$G$"$k!#0J>e$rF'$^$($F%Z!<%8$NJ,N`JiSK!"J,N`4V$NCV49BP>]$H9k=g=x$r<!$Nh&$KM?$($k!#

1) B>$N%W%m%;%9$N6&M-%3%T!<%Z!<%8!" 2) <B9TCf%W%m%;%9$N6&M-%3%T!<%Z!<%8!" 3) B>$N%W%m%;%9$N%i%9%H%o%s!&%Z!<%8!" 4) B>$N%W%m%;%9$N%m!<%+%k%Z!<%8!" 5) <B9TCf%W%m%;%9$N%i%9%H%o%s!&%Z!<%8!" 6) <B9TCf%W%m%;%9$N%m!<%+%k%Z!<%8!"$?$@$7$3$liN87L)$J=g=x4X78$O!"6&M-!&Hs6&M-3FNN0hKD$$$F$N;2>HIQEY$dMFNL!"%W%m%;%9$NAH9g$;!"%M%C%H%o!<%/5Z$SFs<!5-21$N@-

I= **1** %W%m%;%9!&%;%C%H$N35MW

%W%m%;%9 %;%C%H	%W%m%;%9?t	JBNsEY (J#?t$N>l9g$N8D?t)	AmJBNsEY	AmHs6&M- 6u4V%5%$%: [pages]	Am6&M- 6u4V%5%$%: [pages]	%a%b%j$N :GBgMW5aEY [Am<B%a%b%jHf]	F14|4V3V [clocks]
A	12	16,36,48,50(2),64,70 96,100,128,192,200	1050	35500	10120	1.00	1000–2000
K	12	48,96,208,256	1184	49920	6360	1.30	1000
L	11	64(5),128(2),192(2),256(2)	1472	68480	7280	1.68	1000
M	23	16(16),50(6),256(1)	812	35480	30320	1.70	1000

G=$K0MB8$9$k!#

:#2s$N%7%_%e%l!<%7g%s$G$O!"<!$NFsDNCV49J}<0$r<BAu$7 Hf3S$r9T$JC?!#

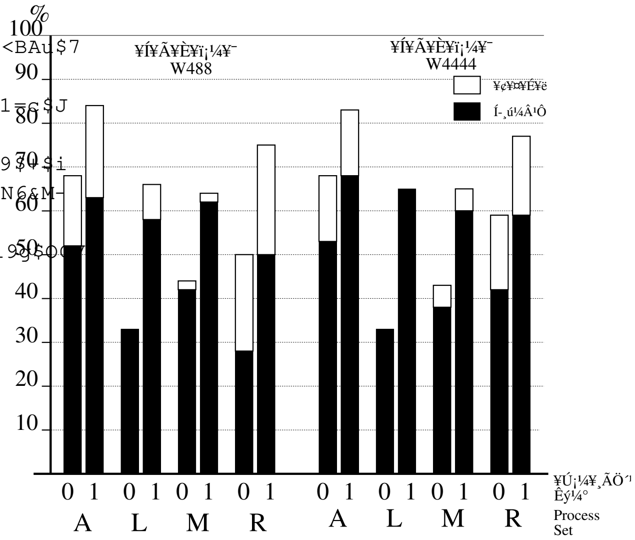
CV49J}<0 **0** %Z!<%8$N<oN`!?%W%m%;%9$N6hJLJ7$KC1=c$J LRU =g

CV49J}<0 **1** %9%1%8%e!<%j%s%0M%@hEY$NDc$$%W%m%;%9Ni 3.2@aK*1k%Z!<%8$N<oN`=g$KA*Br!#3F%W%m%;%9$N6&M- !?Hs6&M-6u4VKh$K%Z!<%8$N LRU =g$r4IM}

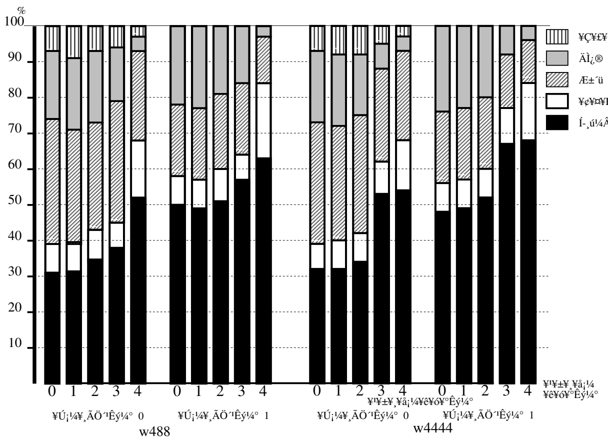
$?$@7IAi$NJ}<0$b!"0l4S@-=hM}Cf$N6&M-%Z!<%8$N>l9g$O CV 49BP>]$H7J$$!#

I= **2** 3F<o%3%9%H$*$h$S%Q%i%a!<%?

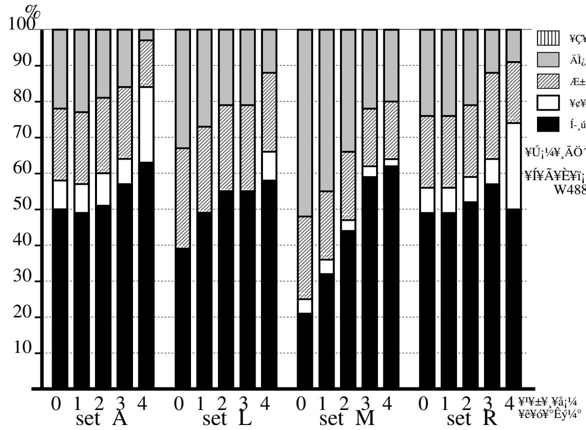
9`L\	CM
%W%m%;%C%5?t	256 Bf
%G%#%9%/%"%/%;%9	100000 clk
%Z!<%80\F04pK\%3%9%H	500 clk
DL?.4pK\%3%9%H	50 clk
1 %a%b%j$N%Z!<%8?t	400 pages
1 %Z!<%8$N%5%$%:	4096 Byte
Am%a%b%jNL	409.6 Mbyte
1 quantum	1000000 clk



?^ **3** %Z!<%8CV49J}<0$NHf3S



?^ **2** %W%m%;%9%;%C%H #A$N%7%_%e%l!<%7g%s7k2L



?^ **4** %W%m%;%9%;%C%H#A!"#L!"#M!"#R$N%7%_%e%l!<%7g%s7k2L

4 7k2L$*$h$S9M;!

<B83H7FOI= 2Nh$&$J%Q%i%a!<%?$r:NMQ$7!" 256 Bf$N%W%m%;%C%5$N 2 DN%7%9%F%`(%k!<%H3,AX$+$i=g$K 8-8-4 J,4t$9$k 3 CJ%M%C%H%o!<%/ [w488 $HI=5-]!"$*$h$SF1 4-4-4-4 J,4t$9$k 4 CJ %M%C%H%o!<%/ [w4444]) $K$*$$$F!"I= 1$N3F%W%m%;%9AH$r<B9T$7 $?!#<B83$O!"%W%m%;%9$,0l$D0J>e=*N;$9$k!J20 %?%$%`%9%i%$%9 J,$NM-8z<B9T8e!K$+!" 100 %?%$%`%9%i%$%9$N<B9T$r=*$(k^$G 7QB3$7$?!#

%W%m%;%9%;%C%H#AKBP9$k<B83$,=*N;7?;~E@GNI>2A7k2L $r?^ 2$N%0%i%U$K<($9!#:8Ns$N%0%i%U$, w488!"1&Ns$, w4444 $N>l9g$N7k2LG"$k!#$^$?!"%Z!<%8CV49J}<0$NHf3S7k2L$r?^ 3$K <($9!#?^ 3$G$O%9%1%8%e!<%j%s%0J}<0#4!" w488 $N%M%C%H%o!<%/ GN%j%b!<%H%a%b%j%"%/%;%9%-%c%C%7%e%R%C%H!"%W%m%;%9%;%C%H#A$*$h$S?^<($7$F$$$J$$$, %W%m%;%9%;%C%H#L!"#M!"#RKD$$$F>o$K0BDj$7$F%9%1%8%e!<%j%s%0J}<0#4$,:G$bM%$1$?@-G=$rM?$($k3H$K4p$E$$$F$$$k!#<!

$K!"%Z!<%8CV49J}<0$NHf3S7k2L$r?^4$K<($9!#$3$3$G$b!"%Z!<%8$NJ,N`$K=>$C$?%a%b%j%Z!<%8CV49J}<0$K$D$$$F=R$Y%8%e!<%j%s%0J}<0#4$rMQ$$$F$$$k!#

4.1 %9%1%8%e!<%j%s%0J}<0KD$$$F

A 0J30$N%W%m%;%9AH$G$O!"6&M-%Z!<%8$N%3%T!<$,@8@.$5lk3H$G%a%b%jCV49$,H/@8$7$F$$$k!#HFMQ$JJ,;6JBNs4D6-$GO3Nh$&$J%7%9%F%`$NMxMQ>u67$,<+A3$G$"$m$&!# algo4 $N$h$&$K%W%m%;%9$N3d$jEv$FNN0h$r8GDj$7$?>l9g!"%W%m%;%9AH$NAH9g$;$N@-<A$+$i==J,$K%W%m%;%C%5$r3hMQ$J$$$?$a!"<B:]$N%7%9%F%`GO%"$$%I%k;~4V$,8:$k2DG=@-H7$F!"0J2<$N3H$,5s$2il$k!#

1. Bf?t2DJQ@)Ls (SSS–$CORE$ KO<BAuM=Dj) $N:NMQ$Khj!"%W%m%;%C%5Bf?tKD$$$F<+M3EY$N9b$$%9%1%8%e!<%j%s%0$r9T$&3H$,$G$-$k!#
2. FCDj$N%W%m%;%9AH$KHC$F%9%1%8%e!<%j%s%0$N"7j"HJ$kNN0h$r!"B>$N%W%m%;%9$,M-8zMxMQ9k3H$,$G$-$k!#

A0=R7?h&$K!" algo2, 3, 4 $N0c$$$O$a%b%j%Z!<%8$N0LCV$K8G<9$9$kEY9g$G$"$k!#<B837k2L$O!"%W%m%;%9$r<B%Z!<%8$r=iM-$9$kNN0h$K3djEvF$k798~$,9b$$J}<0$[$INI$$$3HrJ*8lCF$$$k!# algo2, 3, 4 $N=g$K%Z!<%8$N0\F0NL$,B?$$$o1@$,!"?2$r8+kH!"$=$N=g$GDL?. (%Z!<%8=hM}) $dF14|$,@jak;~4V$,Bg$-$/$JCF$$$k3H$,J,$+$k!#$3lO!";2>HIQEY$N9b$$H$6&M-6u4V%Z!<%8$N0\F0$,>/$J$/$Jkh$&$K%9%1%8%e!<%j%s%0$9$k8z2L$,1F6A$7$?$H?dDj5l$k!#$^$?!"%a%b%j0n$l$,$[Hs$I5/$-$J$$[†1] %W%m%;%9AH A $N>l9g$K$D$$$F$b!"$I$N;XI8$rMQ$$$F$b algo4 $,:GNI$HJC$F$$$k!#$=$l0J30$N%9%1%8%e!<%j%s%0J}<0$O!"7k6I%Z!<%8$N0\F0%3%9%H$,9b$/$D$$$F@-G=$,=P$F$$$J$$!#

4.2 %a%b%jCV49J}<0KD$$$F

%a%b%jCV49J}<0KD$$$F$OJ}<0 1 $,J}<0 0 $K>o$K>!CF$$$k!#J}<0 1 GO%W%m%;%9$N6&M-%Z!<%8$,CV49$5$lkNKBP7$F!"J}<0 0 GO%W%m%;%9$N%m!<%+%k6u4V$N%Z!<%8$d%i%9%H%0%s6&M-%Z!<%8$,CV49$5lF$$$k!#%a%b%jXNMW5aEY$,7Z$$%;%C%H A, K, L GO!"B>?M$N%3%T!<%Z!<%8$rCV49$9$k3H7+$J$$!#b&>/$7%a%b%j$X$NMW5aEY$,=E$$%;%C%H M GO<+J,$N%3%T!<%Z!<%8$rCV49$9$k3Hb"k,!"hj;2>H5l0W$$Hs6&M-%Z!<%8$rDI$$=P5J$$$3HG8zN($NNt2=$rKI$$$G$$$k!#$3$3K"2?%1!<%9GO!"6&M-%3%T!<%Z!<%8$rM%@hE*$KCV49$9$k8z2L$,6K$aFBg-$/$JCF$$$k$H$$$($k!#0J>e$N3H$+$i NUMA 4D6-K*$$$F$O!"%Z!<%8$r%"%/%;%9IQEY$*$h$SCV498e$N:F%"%/%;%9%3%9%H$r9MN8$7$?J,N`$K4p$E$$$?%a%b%jCV49$r9T$&3H$G!"9b8zN($JHFMQ4D6-$rDs6!$9k3H,2DG=G"k3H,<(5l$F$$$k!#

:#2s$N<B83$GbCHb@-G=$NNI$$!"%9%1%8%e!<%j%s%0J}<0 alog4 $GCV49J}<0 1 $N>l9g$N7k2L$G!":GBgM-8z<B9TN($, 65% $+$i 85% DxEYG"$k!#6&M-%Z!<%8$N0l4S@-4IM}$, Sequential consistency $K=>$&$?$a!"%Z!<%8$N%"%C%W%G!<%H=hM}<+BN$N%3%9%Hhj!"6&M-NN0hXN%"%/%;%9=hM}K*1k@h9T%"%/%;%9=hM}$N=*N;BT$A;~4V$,Hs>o$KBg$-$$!#

3l$O4KOB$5l?%a%b%j$b%G%k$N:NMQKh$j>.$5$/$9k3H,2DG=G"$k!#$?$@4KOB$5l?%a%b%j$b%G%k$r;H$($P!"%Z!<%8$r0\F0$7$?;~$N%3%9%H$N%W%m%;%9$KBP9k0-1F6A$N8z2L$Ol/Jk!#

$^$?K\9FK*1k%7%_%e%l!<%7%g%s!&%b%G%kGO!"%a%b%j%"%/%;%9$H%9%l%C%I4V$NF14|H,FHN)7?;v>]H7$F%b%G%k2=$5lF$$$k$?$a!"%Z!<%8=hM}KHqd5l$k;~4V$N8:>/$O!"$=N^$^F14|;~4V$NC;=LKDJ,$k!#

0J>eN3H+$i!"K\9F$K$*$1$k<B83$G$N7k2L$NCMNDc5$O!"JBNs4D6-$K$*$1$k%7%9%F%`$NHFMQ$JMxMQ7ABV$rH]Dj9k3HOJ$$!#

5 $*$ojK

HFMQD6JBNs OS SSS–$CORE$ K*1k;q8;>pJs$rMxMQ$7$?%9%1%8%e!<%j%s%0J}<0!"$JiS$KJ,;66&M-%a%b%j$rA[Dj7?%a%b%jCV49J}<0KD$$$F$O!"%Z!<%8$NJ,N`$K=>$C$?%a%b%j%Z!<%8CV49J}<0$K$D$$$F=RY?!#5iK3li;q8;4IM}5!9=$N@-G=$r!">\:Y3NN(%b%G%k>eGN%7%_%e%l!<%7%g%sKh$jI>2A$7$?!#$=$N7k2L%9%1%8%e!<%j%s%0J}<0KD$$$F$O!";q8;4IM}9=B$$rMxMQ7?!"%W%m%;%9$,=jM-$9$k<B%Z!<%8$,B8:_9kNN0h$r3d$jEvFkJ}<0$NM%0L@-$,G'ai$l!"%a%b%jCV49J}<0$K$D$$$F$O!"%Z!<%8$NJ,N`$K=>$C$?%a%b%jCV49J}<0$,NI$$@-G=$r<($7$?!#$3$NN>J}<0$rAH$_9g$o$;$?>l9g$N<B837k2L$G$O!"Ii2Y>u67$,3d9g9b$$%1!<%9Gb:GBgM-8z<B9TN(Kh$kI>2A$, 65% DxEY0J>e$G!"$3NCMO4KOB5l$?%a%b%j%b%G%k$N:NMQEyKhj5iK8~>e9k3H$,2DG=$G$"$k$H9M$(il$k!#

<U<-

K\8&5f$O>pJs=hM}?66=;v6H2q!J#I#P#A!K$,<B;\$7$F$$$kFHAOE*>pJs5;=Q0i@.;v6H$N0l4D$H7F9TJC$?!%

;29MJ88%

[1] R. Chandra et al. Scheduling and Page Migration for Multiprocessor Compute Servers. In *ACM, ASPLOS VI*, pages 12–24, October 1994.

[2] Intel Supercomputer Systems Division. *Paragon User's Guide*, order number 312489-003 edition, June 1994.

[3] D. G. Feitelson. Packing schemes for gang scheduling. In *Proc. IPPS'96 Workshop on Job Scheduling Strategies for Parallel Processing*, pages 54–66, April 1996.

[4] D.G. Feitelson and L. Rudolph. Distributed Hierarchical Control for Parallel Processing. *IEEE Computer*, 23(5):65–77, May 1990.

[5] J. K. Ousterhout. Scheduling techniques for concurrent systems. *3rd Intl. Conf. Distributed Computer Systems*, pages 22–30, October 1982.

[6] T.E.Anderson et al. Scheduler activations: Effective kernel support for the user-level management of parallelism. *Proc. of the 13th ACM Sympo. on Operating Systems Principles*, 25(5):95–109, October 1991.

[7] R. Vaswani and J. Zahorjan. The implication of cache affinity on processor scheduling. In *Proc. of 13th ACM Symp. on Operating Systems Principles*, pages 26–40, October 1991.

[8] >>K\>0. %^%k%A%W%m%;%C%5>e$NF14|5!9=$H%W%m%;%C%5%9%1%8%e!<%j%s%0$K4X$9$k9M;!. 7W;;5!%"!<%-%F%/%A%c8&5f2qJs9p *No.79-1*, pages 1–8, November 1989.

[9] >>K\>0. :YN3EYJBNs<B9T;Y1g%^%k%A%W%m%;%C%5$N8!F$. >pJs=hM}3X2qO@J8;o, 31(12):37–42, August 1989.

[10] >>K\>0 et al. HFMQD6JBNs%*%Z%l!<%F%#%s%0%7%9%F%` SSS–CORE. F|K\%=%U%H%&%'%"2J3X2qBh *11* 2sBg2qO@J8=8, pages 13–16, October 1994.

[11] $5?.9qM[FsO: et al. HFMQJBNs#O#SN?aN;q8;>pJs$rMxMQ$7$?%9%1%8%e!<%j%s%0J}<0$N8!F$. ?.3X5;Js, 95(210):111–118, August 1995.

[12] $5?.9qM[FsO: et al. HFMQJBNs os *sss–core* K*1k%+!<%M%k%9%1%8%e!<%j%s%0J}<0 — >\:Y3NN(%b%G%kKh$k@-G=I>2A —. >p=h8&Js *96-OS-73*, 96(79), August 1996.

[13] $5?.9qM[FsO: et al. JBNs#O#S$N@-G=M=B,$r2DG=K9$k%7%_%e%l!<%7%g%s%b%G%k. >p=h8&Js *96-ARC-117*, 96(23):19–24, March 1996.

†1 %W%m%;%9$N3d$jEv$FNN0h$N=EJj6q9g$G!"0lItNN0h$K$*$$$F%a%b%jCV49$,H/@8$7$F$$$k!#