HFMQD6JBNs **OS** *SSS–CORE* K*1k;q8;4IM}5!9=
— %9%1%8%e!<%j%s%0J}<0$H%a%b%jCV49J}<0$N@-G=I>2A —

?.9q M[Fs0†: >> K\ >0† J? LZ 7I†

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$$!"%7%9%F%`A4BN$N@-G=$r$"$2$k$3$H$,M-8z$G$"$k!#$^$?J#?t$N%W%m%;%9$,JB9T$KF0:n$9$kHFMQE*4D6-$G$O!"<B%a%b%j$,0n$l$k>l9g$rA[Dj$7$?%7%9%F%`9=C[$,5a$ail$k!# NUMA 4D6->e$GJ,;66&M-%a%b%j$r9=C[$9$k>l9g!"%a%b%j%Z!<%8$r;2>HIQEY$*$h$S:F%"%/%;%9;~$N;2>H%3%9%HKh$j6hJL$9lP!"8zN(E*$JCV49J}<0$,2DG=HJ$k!#K\9F$G$O%a%b%j%"%/%;%9%Y!<%9$N>\:Y3NN(%b%G%k>e$G!"6qBNE*$J%a%b%j4IM}J}<0!?%"%/%;%9IQEY!?%"%/%;%9%3%9%H$rIU2C$7$?%7%_%e%l!<%7%g%s$Khj!"JBNs%W%m%;%9Kh$K=jM-$9$k<B%Z!<%8>pJs$rMxMQ7?%9%1%8%e!<%j%s%0J}<0!"$*$h$S%Z!<%8$NJ,N`$K4p$E$$$?%a%b%jCV49J}<0$NI>2A$r9T$&!#

Resource Management Mechanisms for General Purpose Massively Parallel OS *SSS–CORE*
— Performance of Scheduling and Memory Replacement —

Yojiro Nobukuni,† Takashi Matsumoto† and Kei Hiraki†

Preventing parallel processes from unexpected inefficiencies is a major concern for constructing multiple user/multiple job environment in NUMA systems. Systems can achieve higher performance by using scheduling policies which reflects resource consumption states. For a general environment, which must support concurrent execution of multiple processes, a way is needed to keep systems' effectiveness when physical memories are full. In NUMA systems, memory pages can be classified by access frequencies and required costs for accesses when target pages are not found locally. Selecting victim pages according to the classification enhances system performance. We built a probabilistic model with a concrete memory management scheme and differentiated memory access costs, and simulated processes sets with given access frequencies. The paper describes an evaluation of scheduling policies using resource informations for each process and of page replacement policies based on page coloring under the model.

1. O8aK

NUMA 7?%7%9%F%`$O!"0B2A$J9=@.MWAG$rB??t7k$S$IU$1$FBg5,LO$J%7%9%F%`$r9=C[$7!"9b$$=hM}G=NO$rF@$k3H$,$G$-$kFCD'$r;}$D!#6aG/$N%M%C%H%o!<%/<~JU$N@-G=8~>e$rGX7J$K!"JBNs%"%W%j%1!<%7%g%sN?aN<B9T;Y1g5!9= [13]!"JBNs4D6-2<GN3F<o:GE,2=5;K!$N8&5f!?3+H/ [7] [6] Kh$j NUMA 7?JBNs7W;;5!>eGN9b8zN($GHFMQ@-$r;}C?<B9T7ABV$,2DG=HJCF$-$?!#7+7J$,$i!"HFMQ$J%^%k%A%8%g%V!?%^%k%A%W%m%;%9;HMQ7ABVK*$$$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 [11] $O!"%W%m%0%i%`<B9TC10L$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$FO[$kJ,;64D6-GO!"%9%1%8%e!<%j%s%0$K<B;q8;$N;HMQ>u67$rH?1G$5$;$k3HKh$j!" OS %l%Y%k$Khk%3%9%H$N9b$$%"%/%;%9$r8:>/$5$;$k9b8zN(2=$,2DG=$G$"$k!#

;q8;>pJs$rMxMQ$9$kJ}<0$K!"=8Cf5-217?JBNs7W;;5!8~1N cache affinity J}<0 [14] $,$"k,!"MFNL$N>.$5$J

† E15~Bg3XBg3X1!M}3X7O8&5f2J>pJs2J3X@l96
Department of Information Science, Faculty of Science, University of Tokyo

%-%c%C%7%eGO8z2L$,=P$J$$!#Bg5,LOJ,;64D6->eGO$a
7?;q8;4IM}$r9T$&KO!"3HD%@-$d4IM}8zN($NE@$+$i
3,AX2=5l$?OHAH$,I,MWG"$k!#3,AXE*$J%9%1%8%e!<%j
%s%0$r9T$&bN$K DHC [4] $H Intel Paragon [2] $,$"
$k!# DHC $O Buddy %7%9%F%`$Khk3,AX2=4IM}$r9T
$$!"%i%&%s%I%m%S%s%r4pK\$H7F$*$j!"%W%m%;%9?t$K4p
$E$$$?Ii2Y>pJs [3] N_$rMxMQ$9$k!# Paragon GO=@
Fp$J%W%m%;%C%5J,3d$,2DG=G"k,!";q8;>pJs$OMxMQ$7
$J$$!#$^$?3F%W%m%;%C%5>eGN%9%1%8%e!<%j%s%0$b%+!<
%M%k$,<B9T$9$k!#

5iJk OS Kh$k9b8zN(2=$H7F!";2>HIQEY$*$h$S
:F%"%/%;%9KMW9$k%3%9%H$r9MN8$7$?CV49$r9T$J$&$3$H
Kh$j!"@-G=8~>e$r?^k3H,2DG=G"$k!#J,;66&M-%a
%b%jGO!"Fs<!5-21hj%3%9%H0B$J1s3V%"%/%;%9$,2DG=
$J!"6&M-%3%T!<%Z!<%8$rM%@hE*$KCV49$9$k@oN,$rHk$3
H,9M$($ilk!#

K\9FGOHFMQD6JBNs%*%Z%l!<%F%#%s%0!&%7%9%F%`
SSS–CORE [5] K*1k;q8;4IM}5!9=KD$$$F=R$Y!"
%W%m%;%9$N<B%Z!<%8>pJs$rMxMQ7?%9%1%8%e!<%j%s%0J}
<0JiSK!"%a%b%j%Z!<%8$NJ,N`$KB'C?%a%b%jCV49J}
<0$N%7%_%e%l!<%7%g%s$KhkI>2A$r<($9!#$^$: 2 @a$G
SSS–CORE KD$$$F4JC1$K?($l!" 3 @aG=$N;q8;4IM}
5!9=$r2r@b$9$k!#%7%_%e%l!<%7%g%s!&%b%G%kJiSK<B
837k2LKD$$$FO=l>$l 4 !" 5 @a$G=R$Y!" 6 @a$G$^$H
ak!#

2. SSS–CORE

SSS–CORE [5] $O NUMA 7?JBNsJ,;67W;;5!$rBP>]
H7$?HFMQD6JBNs OS G"$k!#;~J,3d HQ!<%F%#%7%g
%K%s%0$rJ;MQ$7$?%^%k%A%f!<%6!?%^%k%A%8%g%V4D6-$r
6!$7!"JBNs%"%W%j%1!<%7%g%s$N8zN(NI$$<B9T$N<B8=$r
E*H9$k!#

NUMA 7?$NJBNs7W;;5!%7%9%F%`$G$O!"%a%b%j;2>H%3
%9%H$*$h$SDL?.%3%9%H$,$=$N5wN%$K1F6A$5$l!"$^$?$N$l
iNF14|XN8z2L$,Bg$-$/<B9T8zN($K1F6A9k!#$=$3
$G!"JBNs%"%W%j%1!<%7%g%s$N<B9T8zN($r8~>e$9kK$O
3F%9%l%C%I$rF1;~$K%9%1%8%e!<%j%s%0$7!"3d$jEvFi$l
$?MWAG%W%m%;%C%54V$N5wN%$r:G>.2=$7!"<B9T;~$N%a%b%j
%Z!<%8$N0\F0$r:G>.8B$KM^$(k3H,I,MWG"$k!#M^$(
3Nh&$J@-<A$NJBNs%W%m%;%9$r!"J#?tF1;~$KF0$+$9$3
MQ$J4D6-$r9=C[9k$?$aKO!"%*%Z%l!<%F%#%s%0%7%9
%`%l%Y%kKh$k%8%g%V!?%W%m%;%9$r8YC?9b8zN(2=$G
7g$+$;$J$$!#$=$l$r;Y1g$9k?$a *SSS–CORE* GO$C
%f!<%6!?%+!<%M%k4VGN>pJs$N<uEO$7N?aN5!9=$r
6!7F$$$k!# *SSS–CORE* GO3N5!9=$rMxMQ$7!"$k
%a%b%j$N;HMQ>u67$N%9%1%8%e!<%j%s%0XNH?1G!"J1$
$K%f!<%6$+iN%9%1%8%e!<%j%s%0@)Ls$NMxMQ!"$=7F$
@hEY$rMxMQ$7$?;q8;$N8xJ?$J3d$jEvFH$$$&$J}:v$Kh
<B9T8zN($N8~>e$r<B8=7F$$$k!#$^$?5i$K!"%Z!<%8$
J,N`KB'C$?%a%b%jCV49J}<0$b!"F1MM$N5!9=$rMxMQ9
3H$G2DG=$HJk!#<!@aK*$$$F%9%1%8%e!<%j%s%0$
Da%b%jCV49$N6qBNE*$JJ}K!KD$$$F@bL@9k!#

3. *SSS–CORE* $N;q8;4IM}5!9=

3.1 *SSS–CORE* $N%9%1%8%e!<%j%s%0J}<0

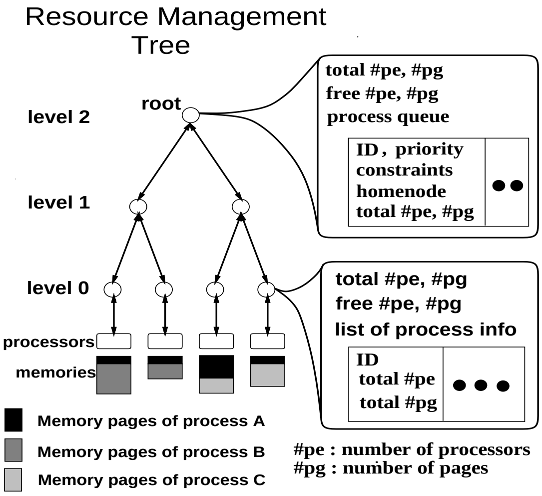
3.1.1 ;q8;4IM}LZ

SSS–CORE $O!"%f!<%6!?%+!<%M%kJ,N%$N 2 %l%Y%k%9
%1%8%e!<%j%s%0$r:NMQ$9$k!#%+!<%M%k$O3F%W%m%;%9$,Ds
<(9k%9%1%8%e!<%j%s%0@)Ls!J3.1.2@a!K$K=>$C$F:G$b
E,Ev$J;q8;$r!"3,AX2=4IM}5l$?;q8;>pJs$rbH$K%W%m
%;%9C10L$K3dEv$F$k!# 2 %l%Y%k%9%1%8%e!<%j%s%0G"$k
$?$a!"3F%W%m%;%9$O3d$jEvFil?;q8;$r<+M3$K:F%9%1
%8%e!<%k9k3H$G!":GE,2=$r?^k3H,2DG=G"$k!#
3,AX;q8;4IM}$r<B8=$9k?$a!" *SSS–CORE* GO2>
A[E*$J;q8;4IM}LZ9=B$$rMQ0U9k!#K\9FK*$$$FO3$l
$r;q8;4IM}LZ$H8F$V!#;q8;4IM}LZ>e$G$O%7%9%F%`A4BN$N
;q8;>pJs$*$h$S!"%W%m%;%9Kh$N;q8;$N;HMQ>u67Ey$r4IM}
9k!#Bg5,LO$J NUMA 7?%7%9%F%`$K$*$$$F$O!"4IM}MQ
;q8;NL$N@)Ls$d4IM}>e$N%\%H%k%M%C%/$r9MN8$9$k$H!"3,
AXE*$J;q8;4IM}$OI,?\G"$k!#;q8;4IM}LZ$O<+?H$N9=B$
$r<B%7%9%F%`$N9=@.$KE,1~$5$;$k3H$G!"MM!9$J%7%9%F
%`$r%5%]!<%H$9k3H,2DG=G"$k!#$=$N7k2L;q8;4IM}
LZ$O!"Nc$($P3,AXE*$K@\B3$5$l$? WS-Cluster K*$$
FOMWAG=hM}AuCV4V$N5wN%$r<+A3$KI=8=$9k3H,$G
$-!"%a%C%7e7k9g$ND6JBNs7W;;5!K*$$$F$OMWAG=hM}Au
CV4V$N5wN%E*$J6aK5$rI=8=$9k3H,G-$k!#$9Jo
$A!"3d$jEvFr9TJ&MWAG=hM}AuCV4V$NDL?.%3%9%H$rGD
0.7?$&$(GN%9%1%8%e!<%j%s%0rb2DG=H7$F$$$k$H
$$$($k!#

;q8;4IM}LZGOO@M}E*$K3F%N!<%IKh$K!"%N!<%I$r%k!<
%HH9$kItJ,LZ$NNN0h$K4^$^lk%W%m%;%C%5$H<B%Z!<%8
$NAm?t$*hS!"%U%j!<$J%W%m%;%C%5$H<B%Z!<%8$NAm?t!"
JiSK%W%m%;%9Kh$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$O$3
Nl$K!"%W%m%;%9Kh$K%9%1%8%e!<%j%s%0@)Ls!"M%@hEY!"
%[%9%`%N!<%I!J8e=R!K$rJ];}$9$k!#?^ 1$K 4 %W%m%;%C%5
$G@.%7%9%F%`$NNc$r<($9!#

3.1.2 %9%1%8%e!<%j%s%0@)Ls

%f!<%6$O!"JBNs2=$5l?%"%W%j%1!<%7%g%s$N@-<A$K$D
$$$F$N>pJs$r;XDj9k!#J]>Z5lkY$-3,AX$N8zN(2=N
%F!<%^$O!"%X$N%5%]!<%HKh$j!"$3$N3FAH$K!"AX$N;q8;
$,%9%1%8%e!<%j%s%0@)Ls$H7F$k%W%m%;%9$N;q8;N&$A
$r%]%j%7!<$GOJ$$!"$=$l$>$l$N%W%m%;%9$+iN;q8;$r
;XDj9k3H$,2DG=$G$"$k!#$^$? *SSS–CORE* GO!"F0E*$J;q8;3d$jEvFNJQ
99$K%W%m%;%9$,BP1~G-kh$&$K!";q8;3djEvF>u67Ey
$rM%!<%M%k$+$i%f!<%6$KDc%3%9%H$G3+<($9$k!#
%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$9k3H,G-$k!#$^$?2DJQBf?t
@)Ls$O>/$7$:$DGb%W%m%;%9$K%W%m%;%C%5$r3djEvF$k



?^**1** ;q8;4IM}LZ

3H$,2DG=$HJk!#Nc$($P==J,$JJBNs@-$,$"$k$?$a$K2D JQ$J%W%m%;%C%5Bf?t$KBP1~$7$F%W%m%0%i%`$5l?%W%m %;%9KBP7FO!"3N@)Ls$,M-8z$KF/$/!#:#2s$N%7%m %l!<%7g%sGO%W%m%;%9$NJBNsEY$OJQ2=7J$$$N$G%7 %1%8%e!<%j%s%0@)Ls$H7F$OBf?t8GDj@)Ls$rMQ$$$k!#

3.1.3 M%@hEY$N7W;;K!

3F%W%m%;%9NM_5aK1hCF;q8;3dEv$r9T$&$?$a!"%W%m %;%94V$N8xJ?@-$rJ]$D5!9=$,I,MWG"$k!# *SSS–CORE* GO@jM-;q8;NL$H%9%1%8%e!<%j%s%0@)Ls$N6/EY$r4p$K%9 %1%8%e!<%j%s%0M%@hEY$r7W;;$9$k!#=>$CF3$NFs4QE@$K $D$$$F8xJ?$J%9%1%8%e!<%j%s%0$,C#@.5l$k!#

SSS–CORE GOM%@hEY$N7W;; [8] [5] K"$?$j!"<! NCMr7W;;9k!# 1) ;HMQ7?;q8;NL" *U* @)Ls>r 7o$N87$7$5: *R*" 3) @)Ls>r7o$NK~B-EY: *S* 0 *or* 1!" 4) L5BLK7$?;q8;NL: *W* 5) BT$A%W%m%;%9$NM-L5: $f_w = 0$ *or* 1!" 6) <cJV$j7O?t: *C* #M%@hEY$OCM$,>.$5 $$$[$I9b$$!#%W%m%;%9Kh$NM%@hEY$N%(%$%8%s%0CM$O!"<! $N<0$Khj5aailk!#

$$aging = (U_r R_c S_c + W_r) f_w * t - C_r(1-t)$$

$^$?M%@hEYNCMNH/;6rKI0$?$a!"D>A0$^$G$9%1%8%e!< %k$5lF$$$?%W%m%;%9$N%(%$%8%s%0$NAmOB$r!"BT$A>uBV $@$C$?%W%m%;%9$K<cJV$jJ,$H7F6QEy$KJ,G[$9$k!#

3.2 %Z!<%8CV49J}<0

J#?t$N%W%m%;%9$,JB9T$KF0:n$9$kHFMQ$J4D6-GO!"<B %a%b%j$,0n$l$k>l9g$rA[Dj7?%7%9%F%`9=C[$,5a$a$i$l $k!#J,;6%a%b%j4D6-%7%9%F%`>e$GJ,;66&M-%a%b%j$rA[Dj 9k$H!";2>HIQEY$*hS:F%"%/%;%9;~$N%"%/%;%9%3%9%H $N0c$$$Khj%Z!<%8$rJ,N`$9$k$3$H$,2DG=$G$"$k!#%Z!< %8$NJ,N`$,G-lP!";2>HIQEY$,>/$J$/:F%"%/%;%9;~$N %3%9%H$,>.$5$$%Z!<%8$+$iCV49BP>]H9$k8zN(E*$J%Z!< %8CV49J}<0$,2DG=$HJk!#

J,;66&M-%a%b%jGO!";2>HIQEYKD$$$F$O6&M-NN0h$G $"$k$+H]$+!"Av9TCf$N%W%m%;%9$N6u4VG"k+H]$+$GJ, N`$G$-$k!#JBNs%W%m%;%9$N>l9g0lHL$K$O6&M-NN0h$N;2>H N($OHs6&M-NN0h$KHf$Y$F>.$5$$!#:F%"%/%;%9;~$N%3%9%H $K$D$$$F$O!"%M%C%H%o!<%/Fb$X$N%"%/%;%9$+!"Fs<!5-21 $X$N%"%/%;%9$G$"$k$+$K$h$C$FJ,N`$,2DG=$G$"$k!#5i K=$N%3%9%H:9$O%*!<%@!<H7$F0c$&$H2>Dj$G$-$k!#$= 3G!"Av9T9k2DG=@-$NDc$$%W%m%;%9$N6&M-%3%T!<%Z!< %8$+$iCV49BP>]$H9k3H$G!"@-G=8~>e$rO+k3H, 2DG=G"$k!#0J>e$rF'$^$($F%Z!<%8$NJ,N`$J$i$S$K!"J, N`4V$NCV49BP>]$H9k=g=x$r<+A3$K<!Nh$&$KM?$($k 3H$,$G$-$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 $N@-G=$K0MB8$9$k!#

CV49J}<0H7FO!"B>$N%W%m%;%9$N%Z!<%8$rCV49BP>] H9$k>l9g (>e5- 1,3,4) $K!"A*Br$9$k%W%m%;%9$N=g=x$K $O!"J#?t$N@oN,$,2DG=$G$"$k!# *SSS–CORE* GO%W %m%;%9$NM%@hEY=g$r4IM}7F$$$k$?$a!"M%@hEY$NDc$$%W %m%;%9$N%Z!<%8$+$iCV49BP>]$H9k3H$,2DG=$G$"$k!#

4. %7%_%e%l!<%7g%s!&%b%G%k

4.1 %b%G%k$N35MW

JBNs%"!<%-%F%/%A%cK*$$$F$O!" OS 5!G=$NI>2AN? aNL?Na%l%Y%k%kEy$NHs>o$K@:L)$J%b%G%k$Khk%7%_%e %l!<%7g%s [12] $O!"HsI>2A%W%m%0%i%`$NG$0U@-$d0lHL @-$+$i;v<B>eIT2DG=G"$j!"%a%b%j%"%/%;%9%b%G%k$K4p E/J}K!$,:G$bE,MQ2DG=$JJ}K!$G$"$k [10]!#K\9FGO I>2A$N@:EY8~>e$rL\E*H7F3l^GN8&5f$GMxMQ$7$? %b%G%k [9] $r3HD%$7!" OS %l%Y%k$N%7%_%e%l!<%7g%s$N $?$a$N4JN,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$$r2> Dj9k!#%M%C%H%o!<%/$OFs=E2=$5l?%9%$%C%A%s%0%M%C %H%o!<%/$G!"%9%$%C%A%s%0$N!<%IK*$$$F%a%C%;!<%8$r %P%C%U%!%j%s%0$9$k%o%s%[%C%WDL?.$r9TJ&!#%N!<%I$O 3F=PNO$KBP7F!"%N!<%IXNF~NO?tJ,$N%(%s%H%j$r;}$D %P%C%U%!$r;}$D!#%Z!<%80\F0$*hS$=$NB>$NDL?.$NFsDL jK$D$$$F!"%N!<%I4V$N 1 %[%C%W$rDL2a9k$?$a$N4pK\ %3%9%H$r%Q%i%a!<%?H7$FM?$($k!#%Z!<%8$N0\F0$*$h$S $=$NB>$NDL?.$KBP7FO=l>$l!"%Z!<%80\F04pK\%3%9 %H$*hSDL?.4pK\%3%9%H$H3F;^$NBS0hG\N(H+$i;;=P$7 $?%3%9%H$rIU2C9k!#?J9TJ}8~$N%P%C%U%!$*hS;^$,6u $$$F$$$J$$>l9gOBT?5l$k!#

%W%m%;%9$OMW5a%W%m%;%C%5Bf?t$HF1?t$N%9%l%C%I$K$h $j9=@.$5lk!#JBNsEY$O0lDj$G!"@8@.;~$+$i=*N;;~$^$G JQ2=7J$$!#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> 6u4VKO!"$=$l$>$lJL!9$N%Z!<%8C10L$N%a%b%j;2>HIQEY

I=$rM?$($k!#3F6u4V$K$*$1$k;2>HNs$O!";2>HIQEYI=Kb$$W%m%;%9$N%9%1%8%e!<%k$OD|ak!#=iaKI,MWBf
1kAmIQEYKBP9$k3F%Z!<%8$N;2>H?trHfH7F3NN($N3NJ]$r;n$_$kNN0h$H!"$=1K<:GT7?>l9g$NBP=hK!
$K@8@.$9$k!#

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
%k$KB’$C$?%"%C%W%G!<%HJ}<0$G!"=>CF%Z!<%8$OCV49$5
lJ$$8B$j%a%b%j$K;D$k!#6&M-%Z!<%8$X$N%"%/%;%9$O%"
%/%;%9;~$K%-%e!<$K7R$,$l!"%i%$%H$N>l9gKO%*!<%J!<
$+$i$N%"%C%W%G!<%H$NAw?.H=lKBP9k Ack $NJV?.
H,9Tol$k!#$^$?%a%b%j;2>H%3%9%H$O!"%/%i%9%?Fb
≪ %/%i%9%?4V ≪ #2<!5-21$H$$$&2>Dj$rH?1G$9kh$&$K
@_Dj9k!#%9%1%8%e!<%j%s%0Kh$j%9%l%C%I$N3djEvF
0LCV$,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$N3d$j
Ev$FNN0h$,JQ2=7?>l9gKO!"8=:_$N3d$jEv$FNN0h30$K
B8:_9k6&M-%Z!<%8$O%3%9%H 0 $G>C5n$9$k!#

%W%m%;%9$N<B9T$O%/%m%C%/%Y!<%9$N3NN(%b%G%k$G!"F1
4|BTAKtO%Z!<%8BT$A>uBV$GJ1lP3F%/%m%C%/Kh$K%a
%b%j;2>H$r9T$J$&!#$^$?%W%m%;%9$N%9%l%C%I$O!"M?$($i
l?M-8z<B9T%/%m%C%/4V3V$G%i%s%@%`$JAH9g$;$N%94IM}
%I4V$GF14|$r5/$3$9!#F14|$O!"F14|E@$XE~C#7?%9%W%m
%I$+$i%i%s%@%`$KA*Br$5l?%P%j%"$N%k!<%H!&%9%l%C
XNAw?.$H!"$=lKBP9kJV?.HG<B8=5l$k!#$3$3$N
M-8z<B9T (;~4V / %/%m%C%/) HO!"%Z!<%8 / F14|BT$A
30$NF0:n$r7? (;~4V / %/%m%C%/?t) N3HG$"$k!#

4.2 %9%1%8%e!<%j%s%0J}<0

A05-%7%_%e%l!<%?>e$K#5$D$N%9%1%8%e!<%j%s%0J}<0$N
<BAu7?!#3FJ}<06&$K!"%?%$%`%9%i%$%9Kh$KM%@hEY$K
;; [8] $r9T$J$$!"M%@hEY$N9b$$%W%m%;%9$+$i=g$K!"$=$l
$>$l0J2<$K<($9J}K!$G%9%1%8%e!<%j%s%0$r9TJ&!#

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

algo1 %7%9%F%`Cf$N%/%i%9%?$rC<$+$i=gKI,MWJ$@$1
3djEvF$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

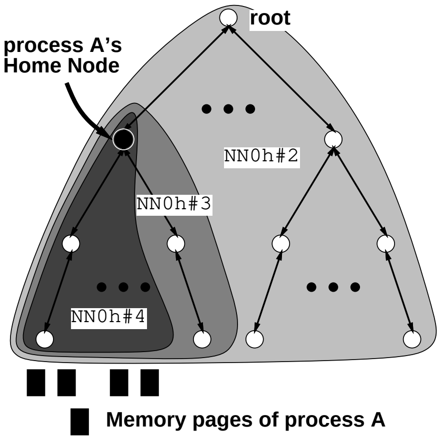
algo3 %[!<%`%N!<%I0J2<$NNN0h$N$_$G%Z!<%8N"$kNN
0h$+$i3djEvF$kJ}<0

algo4 %[!<%`%N!<%I0J2<$NNN0h$G<+J,$N%Z!<%8$,B8$
9kNN0hN_$r3d$jEvFkJ}<0

$?$@$7>e5-$G%[!<%`%N!<%IHO;q8;4IM}LZ>e$N%N!<%I
$G!"%W%m%;%9$NMW5aBf?t0J>e$N%W%m%;%C%5$r4^$`It
$KBP1~$9kbNG!":G2<0L%l%Y%k$K0LCV$9kbNN$3
G"$k!#$9Jo$A%[!<%`%N!<%I$O!"0l$DA0$N%9%1%8%e!<
%j%s%0;~$N3dEvNN0h$rBeI=7F$$$k!#?^2$K%[!<%`%N!
%INNcr<($9!#?^Cf$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

$,0[$JCF$$$k!# 5 DNJ}<0N&$A algo2, 3, 4 $,;q8;



?^2 ;q8;4IM}LZ$H%9%1%8%e!<%j%s%0BP>]NN0h

4IM}LZ9=B$$rMxMQ9kJ}<0G"$k!#$3$N 3 J}<0$N0c$$$O
%W%m%;%9XN%W%m%;%C%5$N3d$jEv$FNN0h$,!";HMQCf$N<B
%a%b%j%Z!<%8$N0LCV$K8G<9$9$kEY9gK"$k!#?^ 2$NNc$G
$ONN0h 2, 3, 4 $,$=l>$l algo2, 3, 4 $,3dEv$r;n$_$k
NN0hG"$k!#$3$3$GNN0h 4 $,A02s
$N3d$jEv$F0LCV$G!"%W%m%;%9 A $,<B%Z!<%8$r=jM-7F
$$$kNN0hG"$k!#$^$?NN0h 3 $,NN0h 4 $KBP1~$9$k%[!<%`
%N!<%IKhCFBeI=5l$kNN0h$G$"$k!# algo4 $N>l9g
KO4pK\E*$K!"%W%m%;%9Kh$N<B%Z!<%8$NB8:_0LCV$KBP1~
9kFKh2sF1$8NN0h$,3djEvFil$k!# algo3 $N>l9g$K
$O!"NN0h 3 K"$?$k%[!<%`%N!<%I0J2<$NNN0hK*$$$F3d
Ev$r;n$_$k!#A02s$N%9%1%8%e!<%k;~$N3d$jEv$FNN0h$,!"
B>$N%W%m%;%9$K4{$K3d$jEv$F:Q$_$J>l9g$K$O!"I,MW$JBf
?t$,3NJ]$G$-$l$P<B%Z!<%8$r;}$?$J$$NN0hG"CF$b!"
NN0h 3 NCfG$"$l$P3d$jEvFk!# algo2 $N>l9g$K$O!"
algo3 $NMWNN$GNN0h 3 $GI,MWBf?t$r3NJ]G-$J$$>l9g
$K!"%7%9%F%`A4BN$KAjEv9kNN0h 2 Fb$N;D$j$NNN0h$G3d
Ev$r;n$_$k!#$7$?$,CF>e5- 3 J}<0$N4V$G$O algo4, 3,
2 $N=g$K<B%a%b%jN"$kNN0h$r3djEvF$k798~$K$"$j!"
$=$N5U=g$G%W%m%;%C%5$NMxMQBf?t$,B?$/Jk2DG=@-$,9b
$$!#3N;0J}<0GO!"BP>]NN0h$KI,MWBf?t$r3NJ]G-$J
$$%W%m%;%9KD$$$F$O!"$=$N;~E@$G$O%9%1%8%e!<%k$5$l
$J$$!# $^$?%W%m%;%9$K3d$jEvFil?%/%i%9%?XN%9
%l%C%I$N%9%1%8%e!<%j%s%0$O!"0J2<NDLjG"$k!#

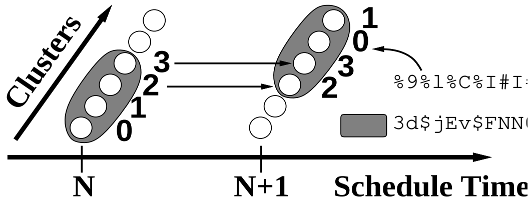
- A02s$N3dEv$H=EJk%/%i%9%?KOA02s$HF1$8%9%l%C
%I$r%9%1%8%e!<%k$9$k
- $=$l0J30$N%/%i%9%?$K$O!";D$j$N%9%l%C%I$r=g$K%9
%1%8%e!<%k9k

---

[y] %W%m%;%9$N<B%Z!<%8$,:F%9%1%8%e!<%k$^$G$K0lIt%/%i%9%?$K$$$F40A4$K%/%i%9%?%a%b%j$+$iDI$$=P5l$?>l9g$K$O!"%[!<%`%N!<%I0J2<$NNN0h!JNN0h 3!K$GB-$j$J$$J,$N%W%m%;%C%5$r3NJ]9k!#

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



?^**3** %f!<%6%l%Y%k!&%9%1%8%e!<%j%s%0Nc

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	10000 clk
%Z!<%80\F04pK\%3%9%H	50 clk
DL?.4pK\%3%9%H	5 clk
1 %a%b%j$N%Z!<%8?t	400 pages
1 %Z!<%8$N%5%$%:	4096 Byte
Am%a%b%j$NL	409.6 Mbyte
1 quantum	100000 clk

?^ 3$K%9%l%C%I!&%9%1%8%e!<%j%s%0NNcr<($9!#?^ 3$N NcGO!"3djEvFNN0h$, N+1 2sL\$H N 2sL\$G=EJC $F$$$kNN0h$N%9%l%C%I 2, 3 O=N^$^%9%1%8%e!<%k$5 $l!"3d$jEv$FNN0h$,JQ2=7?%9%l%C%I 0, 1 KD$$$F$O %9%1%8%e!<%k$5lk%/%i%9%?$,0\F0$7$F$$$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$7$J$1 lPJi$J$$!#=>CF3djEvFNN0h$,$JkY$/=E$Jkh $&$K7?J}$,!"%m!<%+%k%Z!<%8$N0\F0$,>/$J$$!#

J*!"<B9T8zN($N8~>e$rL\E*H7$F;~J,3d$N4V3V$HM-8z $a!J?tI4%_%jIC!A?tICDxEY!K$K@_Dj$9lP!"%9%1%8%e!< %j%s%0KMW9$k7W;;~4V$OAjBPE*$K==J,>.$5$$[!Y] GO==J,$KD9$$;~J,3d4V3V$r2>Dj$7!"%7%_%e%l!<%7%g% GO%9%1%8%e!<%j%s%0$N7W;;~4V$rL5;k9k!#

4.3 %Z!<%8CV49J}<0

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

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

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

J}<0 1 $OAv9TCf0J30$N%W%m%;%9KD$$$F!"M%@hEY$r% MQ$7$?=g=x$E1r9T$&!#M%@hEY$NDc$$%W%m%;%9$N%Z!< $[$I;2>H5lK/$$$@-<A$rMxMQ$7$F$$$k!#$?$@7I@ $NJ}<0$b!"0l4S@-=hM}Cf$N6&M-%Z!<%8$N>l9g$OCV49 H7$J$$!#

5. 7k2L$*$h$S9M;!

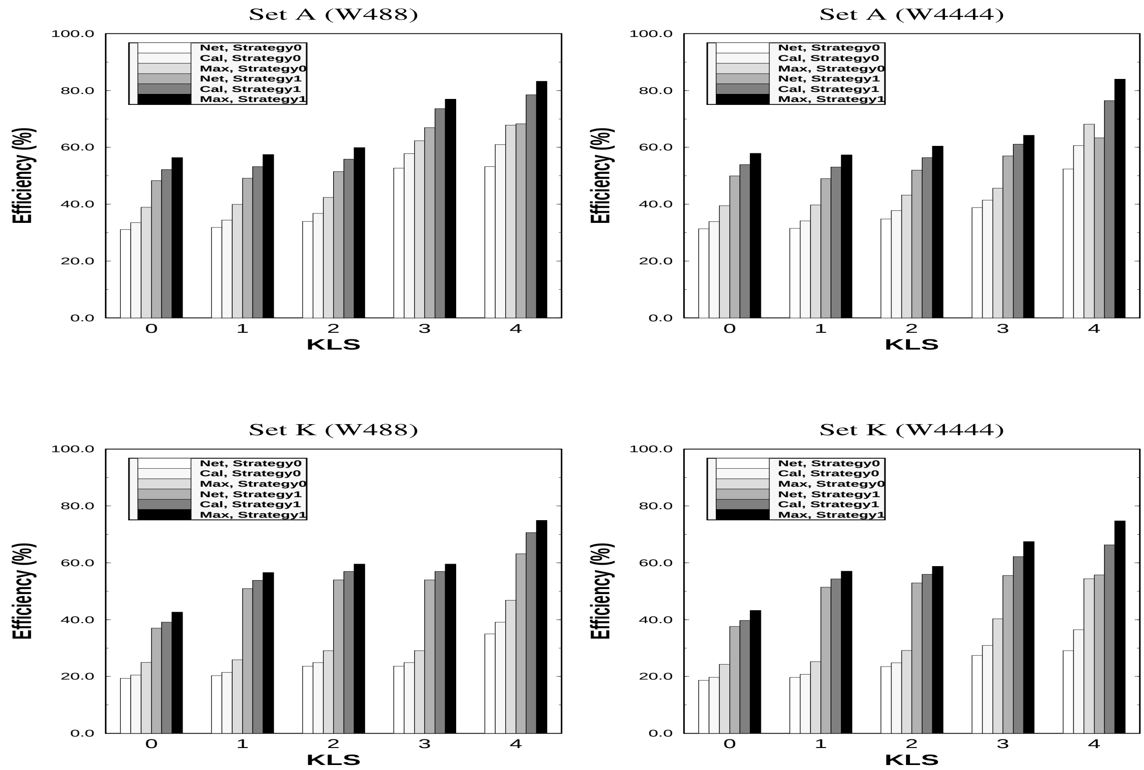
<B83H7FOI= 2Nh$&$J%Q%i%a!<%?$r:NMQ$7!" 256 Bf%W%m%;%C%5$N 2 DN%7%9%F%`(%k!<%H3,AX$+$i= 8-8-4 J,4t$9$k 3 CJ%M%C%H%o!<%/ [w488 $HI=5-]!"$*$h $S$1 4-4-4-4 J,4t$9$k 4 CJ%M%C%H%o!<%/ [w4444]) $K$* $$$F!"I= 1$N3F%W%m%;%9AH$r<B9T$7$?!#$3$3$G$N<B83$N L\E*$O!"%W%m%;%9$N@8@.!&>CLG$K$h$k%7%9%F%`$NIi2YIT 6Q0U$r9MN8$7$?D94|4VK*1k%9%1%8%e!<%j%s%0J}<0$N @-G=$GOJ$/!" OS KHCFC;4|4VGN0lDjIi2Y>uBV$K $*$1$k@-G=I>2A$r9k3HG"$k!#$=3G<B83$O!"%W%m %;%9$,0l$D0J>e=*N;$9$k!J20 %?%$%`%9%i%$%9J,$NM-8z <B9T8e!K$+!" 100 %?%$%`%9%i%$%9$N<B9T$r=*$(k^$G 7QB3$7$?!#$^$?$3$N5,LO$NJBNs%7%9%F%`K*1k OS %l %Y%k$N%7%_%e%l!<%7%g%s$r!"<B;~4V%5%$%:$G9T$&$N$OIT 2DG=$G$"$k!#$=$3$G<B83$O;~4VJ}8~$K05=L$7$F9T$$!"3F <o%3%9%H:9$r%*!<%@!<$N2>Dj$K1h$C$?CM$K@_Dj7?!#

<B83$,=*N;$7$?;~E@$G$NI>2A7k2L$r?^ 4, 5$N%0%i%U $K<($9!#:8Ns$N%0%i%U$, w488!"1&Ns$, w4444 $N>l9g $N7k2L$G$"$k!#3F%0%i%UK*$$$F 6 K\$:DN3F%0%k!< %W$r!"$=l>$l%9%1%8%e!<%j%s%0J}<0 0 $+$i 4 $r:NMQ 7?>l9g$N7k2LG"$k!#3F%0%k!<%WK*$$$F!":8 3 K\$, CV49J}<0 0 $N>l9g!"1& 3 K\$,CV49J}<0 1 $N>l9g$KBP1~ 9k!#3l$i 3 K\$N%0%i%U$O!":8$, “@5L#$NM-8z<B9T N$!"1&$,$=lK%"%$%I%k;~4V$r2C;;7? “:GBgM-8z<B 9TN(”!"Cf1{$,%"%$%I%k;~4V$r@5L#$NM-8z<B9TN(J,$@$1 2C;;7? “Jd@5M-8z<B9TN(” $rI=$9!#

5.1 %9%1%8%e!<%j%s%0J}<0KD$$$F

A0J30$N%W%m%;%9AH$G$O!"6&M-%Z!<%8$N%3%T!<$,@8 @.$5lk3H$G%a%b%jCV49$,H/@8$7$F$$$k!#HFMQ$JJ,;6 BBN4D6-$GO3Nh$&$J%7%9%F%`$NMxMQ>u67$,<+A3G" m&!#IN%W%m%;%9AHK*$$$F$b!"@5L#$NM-8z<B9TN($K hkHf3S$G algo4 $,:GNI$N7k2L$r=P$7$F$$$k!# algo4 Nh$&$K%W%m%;%9$N3d$jEv$FNN0h$r8GDj7?>l9g!"%W%m %;%9AH$NAH9g$;$N@-<A$+$i==J,$K%W%m%;%C%5$r3hMQ$J$$ $?%a!"$3$N3hMQ$5lF$$$J$$J,$r4^$a$?Jd@5M-8z<B9TN($d:GBgM-8z<B9TN($GHf3S9k$H!" algo4 $HB>$NJ}<0$N @-G=:9$O5i$K9-$,$k!#<B:]$N%7%9%F%`GO%"%$%I%k;~

[!Y] *SSS–CORE* GO;~J,3dC10LrBg-aKHk



?^4 %;%C%H A, K $N7k2L (:8Ns:w488, 1&Ns:w4444)

4V$,8:$k2DG=@-H7$F!"0J2<$N3H$,5s$2il$k!#%0$9$k8z2L$,1F6A7?$H?dDj$5lk!#5i$K%W%m%;%9

(1) Bf?t2DJQ@)Ls (*SSS–CORE* KO<BAuM=Dj) $N:N MQ$Khj!"%W%m%;%C%5Bf?tKD$$$F<+M3EY$N9 $$%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-8zMxMQ$9 k3H,G-$k!#

1 GOJd@5M-8z<B9TN(DxEY$N@-G=$r8+9~$a!" 2 GO:$N! $N%1!<%9$G:GBgM-8z<B9TN($^$G$N@-G=$r8+9~$`$3HN0 $-$k!#K\9F$K5s$2$?$4$/0lIt$NFCDj$N%W%m%;%9AH$K$D$$ F@1GJ/!"hjB?MM$J%1!<%9$r9MN8$7$?I>2A$r9T $&$3HO!"HFMQ OS H7FN@-G=JiSK *SSS–CORE* K\Mh$N@-G=$rO@8k>e$GI,MWIT2D7g$G$"$k!#3N9M$($+$iJd@5M-8z<B9TN($d:GBgM-8z<B9TN(GNHf3S$,M-8z$G $"$j!" algo4 $,>o$K:GNI$N7k2L$r=P7F$$$k$H$$$($k!#

4.2@a$G@bL@$7$?$h$&$K!" algo2, 3, 4 $N0c$$$O%a%b%j %Z!<%8$N0LCV$K8G<9$9$kEY9gG"C?!#<B837k2L$O!"%W %m%;%9$r<B%Z!<%8$r=jM-$9$kNN0h$K3djEvF$k798~$, 9b$$J}<0$[$INI$$$3HrJ*8lCF$$$k!# algo2, 3, 4 $NM =g$K%Z!<%8$N0\F0NL$,B?$$$o1@$,!"I= 3$r8+kH!"$- $N=g$GDL?. (%Z!<%8=hM}) $dF14|$,@jak;~4V$,Bg$-$/ JC$F$$$k3H$,J,$+$k!#$3lO!";2>HIQEY$N9b$$Hs6& M-6u4V%Z!<%8$N0\F0$,>/J/Jkh&$K%9%1%8%e!<%j%s

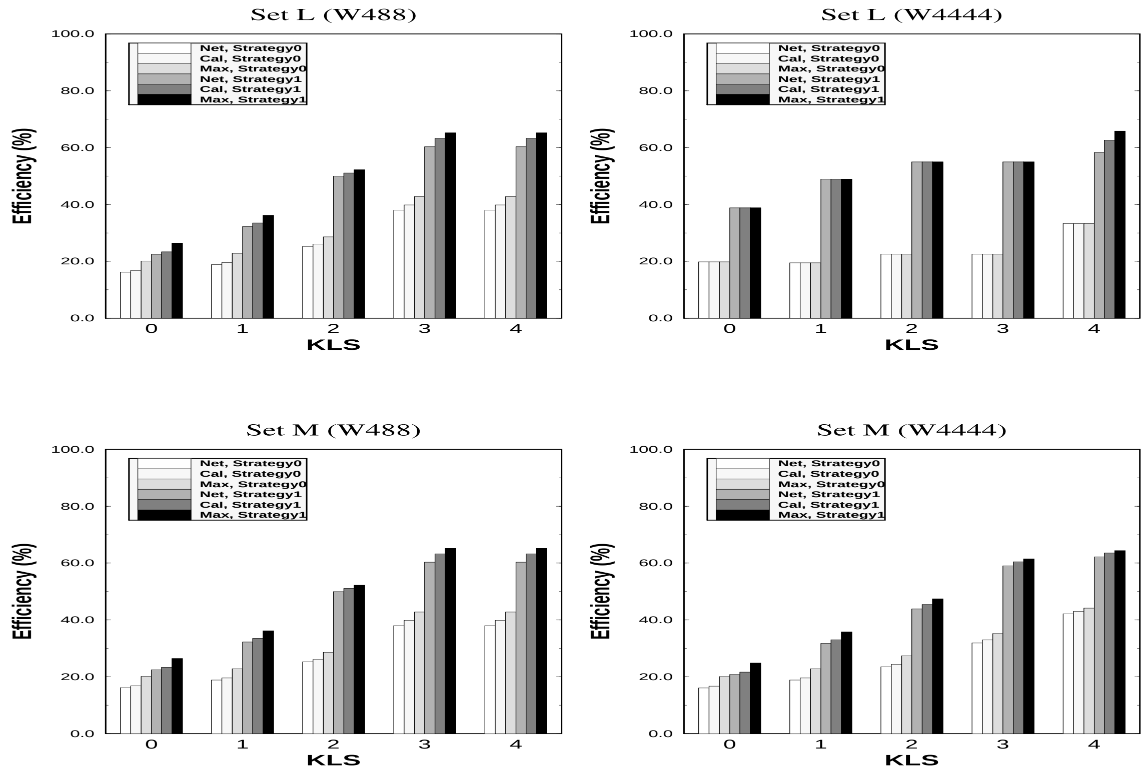
$N3d$jEv$FNN0h$rIQHK$KJQ99$9kH!"3F%/%i%9%?$K3F %W%m%;%9$N%a%b%j$,=8Cf$7F7$^$$!"8_$$$K%Z!<%8 $NC%$$$9g$$$r5/$3$9NL$,A}2C$9k?$a!" algo4 KHfY $$N algo3!" algo2 $,8zN($,0-$/$JCF$$$k!#$^$?!"%a%b $$0nl,$[$HsI5/$-$J$$%W%m%;%9AH A $N>l9g$K$D $$$F$b!"$I$N;XI8$rMQ$$$F$b algo4 $,:GNI$HJC$F$$ $k!#$=$l0J30$N%9%1%8%e!<%j%s%0J}<0$O!"7k6I%Z!<%8 $F0%3%9%H$,9b$/$D$$$F@-G=$,=P$F$$$J$$ (I= 3)!#$5

I=**3** <B9T;~4VFbLu (%)(w488, CV49J}<0 3)

Set	Type	algo0	algo1	algo2	algo3	algo4
	:GBgM-8z	57.89	57.36	60.41	64.22	84.02
	F14|	19.98	19.59	20.84	20.03	12.45
	DL?.	22.10	23.01	18.72	15.70	3.49
	:GBgM-8z	42.65	56.57	59.53	59.53	74.91
	F14|	25.87	22.08	23.24	23.24	17.82
	DL?.	31.46	21.32	17.20	17.20	7.22
	:GBgM-8z	38.81	48.93	54.98	54.98	65.85
	F14|	28.52	24.07	23.58	23.58	22.23
	DL?.	32.64	26.96	21.39	21.39	11.87
	:GBgM-8z	24.79	35.73	47.42	61.47	64.37
	F14|	22.83	19.03	18.68	16.57	16.06
	DL?.	52.36	45.21	33.86	21.90	19.51

$?$@7G%#%9%/%"%/%;%9;~4V$r=|$/

$W%m%;%9$N3djEvFNN0h$N=E$J$j6q9g$G!"0lItNN0hK*$$$F%a%b $jCV49$,H/@8$7$F$$$k!#



?^5 %;%C%H L, M $N7k2L (:8Ns:w488, 1&Ns:w4444)

$F!"CV49J}<0 1 $G@5L#$NM-8z<B9TN($N7k2L!J%0%$
Cf3F%0%i%UFb1&$+$i#3$DL\!K$r8+kH!" algo2=algo3
HJCF$$$k%1!<%9 (K, W488; L, w44444) $, 2 $D!"
algo3=algo4 HJCF$$$k%1!<%9 (M, L; w4444) $, 2
D"$k!# algo2, 3, 4 GO!"%7%9%F%'$N3,AX@-$rH?1G$5
$;$?;q8;4IM}9=B$$rMxMQ7F%9%1%8%e!<%j%s%0$r9T$&$?
$a!"%W%m%;%9$X$N3d$jEv$FNN0h$r4IM}LZ$NItJ,LZ$NH
$G8BDj$9k3H,G-$k!#$=3G%9%1%8%e!<%j%s%0$
$,0[$JCF$b!"%W%m%;%9$NAH$_9g$o$;$KhCFOEy$
%9%1%8%e!<%j%s%0$r9T$C$F$$$k!# algo4 GO3NNN0h$r
8BDj9kFC<A$r!"%a%b%j$NMxMQ>u67$N>pJs$HJ;$;$k$
G"if$k%W%m%;%9$KBP7FMxMQ9k3H$,2DG=$HJ
F*$j!";q8;4IM}9=B$$rF3F~7?MxE@$,H/4x$5lF$
$k!#

5.2 %a%b%jCV49J}<0KD$$$F

%a%b%jCV49J}<0KD$$$F$OJ}<0 1 $,J}<0 0 $K>o$K>H$
$F$$$k!#@-G=$NNI$$ algo4 $N>l9g$K$*$$$F!" w488 N
83GN3F%W%m%;%9AHGNCV49$NMM;R$rI=4$K<($9!#
J}<0 1 GO%W%m%;%9$N6&M-%Z!<%8$,CV49$5$lkNK
7F!"J}<0 0 GO%W%m%;%9$N%m!<%+%k6u4V$N%Z!<%8$
%9%H%o%s6&M-%Z!<%8$,CV49$5lF$$$k!#%a%b%jXNMWD
EY$,7Z$$%;%C%H A, K, L GO!"B>?M$N%3%T!<%Z!<%8$
CV49$9$k3H7+$J$$!#b&>/$7%a%b%j$X$NMW5aEY$N
$$%;%C%H M GO<+J,$N%3%T!<%Z!<%8$rCV49$9$k3H$b

$%Uk$,!"hj;2>H5l0W$$Hs6&M-%Z!<%8$rDI$$=P5J$$
3H$G8zN($NNt2=$rKI$$$G$$$k!#$3$3K"2?%1!<%9$G
$O!"6&M-%3%T!<%Z!<%8$rM%@hE*$KCV49$9$k8z2L$,6KaF
Bg$-$/JC$F$$$k$H$$$($k!#
J>eN3H+$i NUMA 4D6-$K$*$$$F$O!"%Z!<%8$r%"
%9IQEY$*$h$SCV498e$N:F%"%/%;%9%3%9%H$r9MN8$7$?
CQNO$K4p$E$$$?%a%b%jCV49$r9T$&3H$G!"9b8zN($JHFMQ
4D6-$rDs6!$9k3H,2DG=G"k3H,<(5l$F$$$k!#

5.3 $$ HFMQJBNs4D6-$N2DG=@-$K$D$$$F

r#2s$N<B83$GbCHb@-G=$NNI$$!"%9%1%8%e!<%j%s%0
J}$H alog4 $GCV49J}<0 1 $N>l9g$N7k2L$G!":GBgM-8z<B
9TN($, 65% $+$i 85% DxEYG"$k!#6&M-%Z!<%8$N0l4S
@-4IM}$, Sequential consistency $K=>$&$?$a!"%Z!<%8
$N%"%C%W%G!<%H=hM}<+BN$N%3%9%Hhj!"6&M-NN0hXN%"
%/%;%9=hM}K*1k@h9T%"%/%;%9=hM}$N=*N;BT$A;~4V$,
HsoKBg$-$$!#3l$O4KOB$5l?%a%b%j$b%G%k$N:NMQ$K
hj>.5/9k3H$,2DG=$G$"$k!#$?$@4KOB5l$?%a%b
%j%b%G%k$r;H$($P!"%Z!<%8$r0\F0$7$?;~$N%3%9%H$N%W%m
%B%9KBP9$k0-1F6A$N8z2L$O>.$5$/$J$k!#$7$+$7:#2s$N
<B83GO!"%W%m%;%9$N6&M-NN0h$X$N%"%/%;%9$N($r>.$5$/
7F$"$j (1–3%)!"B?MM$J%"%W%j%1!<%7%g%s$r9M$((
$?>l9g$K$O!"%9%1%8%e!<%j%s%0J}<04V$N@-G=:9$N8=$lJ}
$,=8~$KJQ2=OJ$$$H?dDj9k!#5i$K!"4KOB$5l?%a
%b%j%b%G%k$N>e$G6&M-NN0hXN%"%/%;%9$N($,9b$$%"%W%j

I=**4** %Z!<%8<oN`Kh$NCV492s?t (algo4, w488)

CV49 J}<0	%W%m %;%9 AH	%Z!<%8<oN` other's copy	own copy	other's last	other's local	own last	own local
	A	10944	4770	723	4763	303	1130
	K	33105	10487	830	22598	65	3803
J}<0	L	92253	18063	4911	63885	136	9978
1	M	46394	23581	6873	11725	4054	6577
	A	38976	0	0	0	0	0
	K	77665	0	0	0	0	0
J}<0	L	414287	0	0	0	0	0
3	M	245705	11578	0	0	0	0

%1!<%7%g%sKD$$$F$O!"3F<o%3%s%Q%$%k5;=Q$H3,AX2=%^%k%A%-%c%9%H$d Ack $N%3%s%P%$%K%s%0$H$$$C$?DL?.5;=Q$rAH9go;$FF3F~$9k3HKhj!"<B9T8zN($N8~>e$rO+k3H,2DG=G"$k!#

$^$?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$$$k$?$a!"%Z!<%8=hM}KHqd5l$k;~4V$N8:>/$O!"$=N^$^F14|;~4V$NC;=LKDJ,$k!#0J>e$N3H$+$i!"K\9FK*1k<B83GN7k2LNCMNDc%`$5$,!"JBNs4D6-$K$*$1$k%7%9%F%`$NHFMQ$JMxMQ7ABV$rH]Dj$9k3HO$J$$!#

6. $* $o $j $K

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$rA[Dj7?%a%b%j%Z!<%8$NJ,N`$K=>C?%a%b%j%Z!<%8CV49J}<0KD$$$F=RY?!#5iK3li;q8;4IM}5!9=$N@-G=$r!">\:Y3NN(%b%G%k>eGN%7%_%e%l!<%7%g%sKh$j!2A$7$?!#$=$N7k2L%9%1%8%e!<%j%s%0J}<0KD$$$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!#

K\Mh$OAjMF$l$J$$JBNs%"%W%j%1!<%7%g%s$N8zN(E*<B9T$H8z2LE*$JHFMQ@-$N<B8=$r9M$($?$H$-!"<B;q8;$,J,;6G[CV5l$kBg5,LO NUMA 7?%7%9%F%`$K$*$$$F$O!"%"%W%1%1!<%7%g%s$K$h$k0B2A$J;q8;MxMQ%3%9%H$NJ]>Z$H!";q8;4IM}$K$*$1$k%\%H%k%M%C%/$NGS=|$,=EMW$H$J$k!#$5$i$K!"$"$kDxEY$N9bIi2Y>uBV$K$*$1$k%7%9%F%`@-G=$NJ]>Z$bI,?\$G$"$k!#K\9F$G=R$Y$? *SSS–CORE* $G:NMQ$9$k%9%1%8%e!<%j%s%0J}<0$JiS$K%a%b%jCV49J}<0$O!">e5-$NL\E*$r<B8=9k;q8;4IM}5!9=$N=EMW$JMWAGHJkbNG$"$k!#K\8&5fK*1kI>2ArDL7$F!" NUMA 7?%7%9%F%`>e$K9b8zN($JHFMQ4D6-$rDs6!$9$k<B:]E*$J%*%Z%l!<%F%#%s%0%7%9%F%`$N;q8;4IM}5!9=$N2DG=@-$r<($9$3H,G-$?!#

<U<-

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

;2 9M J8 8%

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