L?Na>v$_9~$_5Z$S%G!<%?Ej5!$rMQ$$$?Java %W%m%;%C%5$N9=@.J}<0$HI>2A

Evaluation of Java processor using instruction folding and value prediction

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J?@.12G/27n15F|

FbMF9<35

Java 8@81$O6aG/%M%C%H%o!<%/$G;HMQ$5$1$k8@81$NI8=`E*$JCO0L$r@j$a$k$K;j$j!"$=$NMQES$O I}9-$$!#Java 8@81$,$3$1$[$I$^$G$KIa5Z$7$?MW0x$O%W%i%C%H%U%)!<%`$rA*$P$:F0:n$7!"$+$D0BA4$J<B9T4D6-$rDs6!7F$$$kJava $N<B9T4D6-$K$"$k$H8@$($k!#Java <B9T4D6-$N4pK\$HJC$F$$$kNOJava Virtual Machine(JVM) $H8F$P1k2>A[$N7W;;5!$G$"$k!#K\8&5fGOJVM $r%O!<%I%&%'%"$G9=@.$7!"4pK\E*$JJVM ;EMM$K2C$($F9bB.%"%I%l%9JQ49I=$rDs0F$7!"%-%&%C%7%e9=@.$K$D$$$F$b9M;!$r=EM?!#9$9$KJVM $NFCD'$rB*$($?9bB.2=$rL?Na>v$_9~$_$*hS%G!<%?Ej5!$N2$D$NJ}<0$+$i8!F$$7$?!#

$^$:L?Na>v$_9~$_KD$$$F@bL@9k!#JVM $OJ,;64D6-2<$G$N<B9T$rA[Dj7F!"<B9T$U!%$%k$N%3!<%I8zN($,9b$/$Jkh$&!"1i;;$r%9%?%C%/>e$G9T$&%9%?%C%/%"!<%-%F%/%A%c$r:NMQ$7$F$$$k!#9JoA!"HFMQ%1%8%9%?$OB8:_$7$J$$$;EMMKJCF$$$k!#%9%?%C%/%^%7%sGO1i;;L?Na$NA08e$KDj7?E*$J=hM}$,IU2C$5$1k3H,B?$$!#$3$1$O%G!<%?$NF~NO/=PNO$,A4$F%9%?%C%/%H%C%W$K8BDj$5$1$F$$$k$+$iG"$j!"1i;;$NA0$OF~NO$9$k%G!<%?$N%9%?%C%/%H%C%WXN%m!<%I!"1i;;8e$O1i;;7k2L$,=PNO$5$1$?%9%?%C%/%H%C%W$+$i7k2L3JG<@h$X$N%9%H%"$,B?$/8=$1k3HHJk!#3Nh&$J1i;;A08e$ND j7?E*=hM}$r:o8:$9k?aK$O!"%G!<%?$rD>@\1i;;4o$KF~NO$71i;;7k2L$rD>@\3JG<@h$X=PNO9k$H$$$C$?!"Dj7?E*$J=hM}$H1i;;L?Na$H$r0l3g$7$F<B9T$9kh$&$J5!9=$r%W%m%;%C%5>e$X@9$j9~$`I,MW$,$"$k!#$3$N$h$&$J<jK!$O1i;;A08e$NDj7?E*=hM}$r3K$H$J$k1i;;L?Na$K>v$_9~$`3H$+$i!V?Na>v$_9~$_!W$H8F$P1F$$$k!#K\8&5fGO%m!<%+%kJQ?t$rJ];}$9k3HrL\E*H7$?%1%8%9%?$rMQ0U$7!"%m!<%+%kJQ?t%1%8%9%?$rMQ$$$F1i;;4o$XD>@\=PNO/F~NO$9$k5!9=$r9M0F7?!#JVM $CO7$&:n6HNN0h$,8BDj$5$1$F$*$j!"%m!<%+%kJQ?t%1%8%9%?$,$=$NFbMF$N0lIt$rJ];}$9k@1G1i;;N[HsI$NItJ,$r%1%8%9%?4V$G9T$&3H$,2DG=$HJk!#$=$N>l9g!"1i;;KI,MWJCM$rD>@\1i;;4o$KF~NO$7!"1i;;7k2L$rD>@\%m!<%+%kJQ?t%1%8%9%?$X=PNO$9$k!#$3$1$KhjK\MhI,MWG"C?1i;;A08e$N=hM}$rG$$9k3H,2DG=HJC?!#

<!$K%G!<%?Ej5!$K$D$$$F@bL@9k!#%G!<%?Ej5!HO%Q%$%W%i%$%s%9%H!<%k$N860x$HJC$?%G!<%?0MB8L?Na$,;HMQ9k%H%o0MB8L?Na$N<B9T7k2L$r2a5n$N<B9T7k2L$NMzNrKbHE$$$F;vA0$KM=B,$7!"$=$NM=B,CMrbHK0MB8L?Na$rEj5!E*<B9T$9k3HKhC$F%9%H!<%k$r2sHr9kbNG"$k!#Ej5!E*<B9T$HJB9T7FHc0MB8L?Na$r<B9T$7!"$=$N7k2L$,=P$?H3mGM=B,CM$H@5$7$$CMHrHf3S$7!"Ey$7$1$1$PEj5!E*<B9T$O@.8yG"$j!"0z$-B3$-<B9T$rB3$1$k!#7+$7M=B,$r4V0c$($?H-$OEj5!E*<B9T$O<:GTG"$j@5$7$$CM$rMQ$$$F0MB8L?Na$+$i:F$S<B9T$r:F3+9k!#%G!<%?Ej5!$,@.8y$7$?$H$-$O%Q%$%W%i%$%s%O%6!<%I$r2sHr$9k3H,G-!"<:GT7?H-$O!"%Q%$%W%i%$%s%9%H!<%k$,@8$8$?H-$HF1$87k2LHJ

$k!#K\8&5f$G$O%-%&%C%7%e%_%9$Khk<g5-21%X$N%G!<%?%"%/%;%9$N:]$K@8$8$k%Q%$%W%i%$%s%9%H!<%k$N:o8:$r<g$JL\E*H7$F%G!<%?Ej5!$N8z2LrB,Dj7$?!#

0J>e$K=R$Y$?2$D$NJ}<0$r<B:]$KJava 2>A[%^%7%s$G$"$kKaffe>e$K<BAu$7!"B,Dj$r9T$$<!Nh$&$J7k2L$rF@$?!#$^$:L?Na>v$_9~$_KD$$$F$O%W%m%;%C%5FbIt$G:G9b42%!"J?6Q31%bNL?NaH/9T$r:o8:$9k3HK@.8y7?!#%G!<%?Ej5!KD$$$F$O%F%(%*%9%F%C%W?t$G:GBg59%!"J?6Q52%$N%Q%$%W%i%$%s%9%H!<%k$r2sHr9k3H$,$G$-$?!#

:G8e$KK\O@J8$G$O!"L?Na>v$_9~$_$*hS%G!<%?Ej5!$N2<jK!$K2C$($F!"%-%&%C%7%e$d%"%I%l%9JQ49I=$N8z2L$b9M;!$KF~l?%5%$%/%k?t$G$N8z2L$rB,Dj7?!#3N7k2L!"L?Na>v$_9~$_GO:G9b24%!"J?6Q13%$N%5%$%/%k?t$r:o8:$7!"%G!<%?Ej5!GO:G9b29%!"J?6Q18%$N%5%$%/%k?t$r:o8:$9kH$N7k2L$rF@$?!#0J>e$N7k2L$+$i!"L?Na>v$_9~$_$N8z2L$O6KaF9b$$$bNN%G!<%?Ej5!$O%G!<%?M=B,$NE*CfN($,Dc$/!"8z2LO5$[$I9b$/$J$$$H8@$($k!#%G!<%?Ej5!$N8z2L$r9bak$?$a$K%G!<%?M=B,$NE*CfN($N9b$$J$k8~>e$r?^k3H,I,MWG"$k!#

Abstract

Lately,Java becomes the standard network language. It is widely used for web browser,Java-embedded machine, and so on.Java runs on any platform wherever Java Virtual Machine (JVM) — "Virtual" machine which interpret Java byte-code — is implemented.JVM ensures secure execution and dynamic loading. In this research,we chose to implement JVM as a hardware which holds 3 types of fast address translation tables and 2 types of caches in order to improve the performance of its execution speed. Furthermore , we investigated 2 techniques called "Instruction Folding" and "Value Prediction".

Firstly,Instruction folding reduces instructions by folding stack operations and computational operation into one operation.JVM is a stack machine with no registers. Consequently,Java byte-codes,which are interpreted and executed on JVM, is quite simple. Java byte-codes can be easily transfered on the network. On the other hand,JVM allows byte-codes to access only to the stack-top. This causes a lot of loads/stores on the stack top before/after computational,branch,and heap access operations. Using registers which keep local variables of each methods, we can fold these loads/stores into computational,branch,and heap access operations.That is, instead of pushing/popping data on the top of the stack, we directly input registers to ALU and output the result to registers.

Secondly,we measured the performance of data speculation. Data speculation reduces pipeline hazard by predicting the result of instructions caused hazards. Data speculation speculatively execute the following operations using the predicted value,while the instruction caused hazards continue to execute. When it finishes,we compare the predicted value and the right value. If the prediction turn out to be correct,speculative execution ends in success and it can keep executing.If it isn't,prediction was wrong and execution restarts from the dependent instruction. In this research,we used last value prediction and focused on reducing hazards caused by cache miss hits.

We implemented both Instruction folding and Data speculation on Kaffe,a free JVM ,and measured the performance.We used SPEC-JVM98 for benchmarks.As a result,by Instruction folding,our research shows 31% of inner instruction issues were reduced in the average. As for Data speculation,we got rid of 52% of pipeline stalls in the average, 59% at the maximum.

In addition to that,we measured the performance of both Instruction folding and Data speculation by execution cycles. This time, we considered the performance of our fast address translation tables and caches. Result shows,Instruction folding reduced in the average 13% of all cycles executed,24% at the maximum,where Data speculation reduced 18% in the average,29% at the maximum.From this result,we come to the conclusion that Instruction folding improves the performance significantly,while Data speculation needs some additional approach for its better performance.

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1 O8aK **3**

2 Java 2>A[%^%7%s$H**SPEC-JVM98** $NFCD' **4**
2.1 Java 2>A[%^%7%s(JVM) 5
2.1.1 %l%8%9%?%l%9"!<%-%F%/%A%c 5
2.1.2 %R!<%WNN0h 7
2.2 SPEC-JVM98 7

3 9bB.**Java** %W%m%;%C%5$N4pK\9=@. **7**
3.1 %Q%$%W%i%$%s9=@. 7
3.2 %R!<%W;2>H$*$h$S%a%=%C%I8F$S=P$79bB.2=$N$?$a$NJQ499I= . . . 9
3.3 JQ499I=$NM-8z@- 10
3.4 %*%Z%i%s%I%9%?%C%/!"%m!<%+%kJQ?t!"%R!<%W$N;2>H9bB.2=$N$?$a$N%-%c%C%7%e5!9= 10
3.4.1 %*%Z%i%s%I%9%?%C%/$*$h$S%m!<%+%kJQ?t%-%c%C%7%e 10
3.4.2 %R!<%W%-%c%C%7%e 12

4 L?Na>v$_9~$_$*$h$S%G!<%?Ej5!$N$?$a$N3HD% **12**
4.1 L?Na>v$_9~$_$N86M} 12
4.2 L?Na>v$_9~$_$N<BAu 12
4.3 %G!<%?Ej5!$N86M} 14
4.4 %G!<%?Ej5!5!9=$N<BAu 14

5 9bB.2=<jK!$NDjNIE*I>2A **16**
5.1 F0E*%9%F%C%W?t$K4p$E$/L?Na>v$_9~$_$NDjNIE*I>2A 16
5.2 %G!<%?Ej5!$NDjNIE*I>2A 16
5.3 7k2LCM$N6I=j@-$K4X9kI>2A . . 18
5.4 %5%$%/%k?tC10L$GB,Dj7?Java %W%m%;%C%5$NI>2A 18
5.4.1 B,Dj>r7o 18
5.4.2 B,Dj7k2L 19

6 $*$ojK **21**

7 O"B3**2** L?Na=P8=IQEY0lMw **22**

1 O8aK

%$%s%?!<%M%C%H$N5^B.$J3HBg$HHb$K!"$h$j9bEY$J%"%W%j%1!<%7%g%s$,%M%C%H%o!<%/>e$G5aailDD"$k!#$3Nh$&$JGX7JNJ$+!"%M%C%H%o!<%/4D6-$KE,7?8@8lH7$FJava 8@8l$,@_7W5l$?!#Java 8@8l$O%*%V%8%'%/%H;X8~7?8@8lG"$j!"%3%s%Q%$%iKhCFJava %P%$%H%3!<%I$KJQ49$9$k3HKh$j<B9T2DG=$HJk!#Java %P%$%H%3!<%I$K$O%M%C%H%o!<%/$H$$$&4D6-$KE,9g$9k?aNMM!9$J9)IW$,J5lF$$$k!#$^$:%W%m%0%i%`%3!<%I$NBg$-$5$,>.$5$/!"J?6Q$7$FC++$NH>J,DxEY$N%5%$%:$K<}$^$k!#$3$N$?$a%M%C%H%o!<%/$K$*$$$F%U%!%$%k$NE>Aw$r9bB.$K9T$&$3$H$,$G$-$k!#$^$?Java 8@8l$O%W%m%0%i%`$N2~JQ$KBP9k0BA4@-$rJ]>Z$9k3H,G-k?$a!"%M%C%H%o!<%/>e$N%W%m%0%i%`$N$d$j$H$j$KE,$7$F$$$k!#$5$i$KMM!9$J%W%i%C%H%U%)!<%`>eK*$$$FF0:n7d$9$$$h$&C1=c$J;EMMHJCF$$$k!#

Java %P%$%H%3!<%I$OJava Virtual Machine(0J8eJVM) $H8F$Plk2>A[$N7W;;5!>e$GF0:n5;k3HrG0F,K*$$$F@_7W5l$F$$$k!#JVM $r%W%i%C%H%U%)!<%`>e$K9=C[$9$k$3$H$K$h$j!"Java %P%$%H%3!<%I$r<B9T$9$k$3$H$,2DG=$H$J$k!#Nc$($P%$%s%?!<%M%C%H%V%i%&%6$G$"$k%M%C%H%9%1!<%W!&%3%_%e%K%1!<%?!"%$%s%?!<%M%C%H(%/%9%W%m!<%i!"%*%Z%l!<%F%#%s%0%7%9%F%`Solaris $KJVM OAH_3^lF$$$k!#

5F!"Java %P%$%H%3!<%I$N<B9TKOBg$-$/4DNJ}<0$,$"$k!#

%$%s%?%W%j%?J}<0 Java %P%$%H%3!<%I$rC`<!2r<a!&B9T$9$kJ}<0$G$"$k!#;HMQ9k%a%b%j

$O>/$J$$bNN<B9TB.EY$,CY$$!#

@EE*L?NaJQ4%J}<0 Java %P%$%H%3!<%I$r$"$i$+$8$a%M%$%F%#%V%3!<%I$K@EE*$KJQ4%7F$+$i<B9T9kJ}<0G"$k!#<B9T;~$N%P%$%H%3!<%IJQ4%%*!<%P!<%X%C%I$,$J$/<B9TB.EY$N9bB.2=$,K>$akbNN!"%M%C%H%o!<%/>eGNF0E*$J5sF0(%@%$%J%_%C%/%m!<%G%#%s%0)$KBP1~$G$-$:!"$^$?Java 8@81$NFCD9$G$"$k%W%i%C%H%U%)!<%`Hs0MB8!&BA4!&3%s%Q%/%H$J<B9T%U%!%$%k!"$H$$$C$?MxE@$r@8$+$9$3$H$,$G$-$J$$!#

F0E*L?NaJQ4%J}<0(**Just In Time compiler**) 4pK\%V%m%C%/Ey$rC10L$H7F!"%P%$%H%3!<%I$r%M%$%F%#%V%3!<%I$KJQ4%7J$,$i<B9T9kJ}<0G"$k!#%P%$%H%3!<%I$N=i2s$N<B9T;~$KL?NaJQ4%%*!<%P!<%X%C%I$,@8$8$kbN$N!"0J8e7+$jJV$7<B9T$9kH$-$O4{$KJQ4%$5$1$?%M%$%F%#%V%3!<%I$r<B9T9k3HKh$j9bB.2=$9k3H,G-$k!#F0E*$KL?Na$rJQ4%$9k3H+$i%@%$%J%_%C%/%m!<%G%#%s%0KbBP1~9k3H$,$G$-$k!#%$%s%?%W%j%?$HHf3S7FLs10-20 G\DxEY$N9bB.2=$,2DG=G"kbNN!";HMQ9k%a%b%j$O?t%a%,%P%$%H$KC#$9k?$a!"AH$_9~$_MQES$K$OE,$5$J$$!#$^$?L?NaJQ4%%*!<%P!<%X%C%I$rM^$(k?aK!"%M%$%F%#%V%3!<%I$N:GE,2=$,?^$1$J$$7gE@b"$k!#

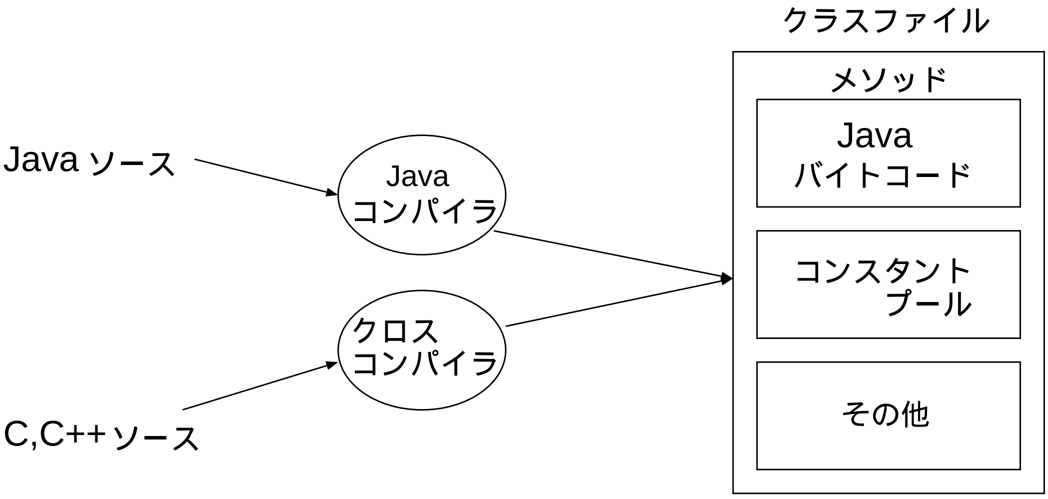
%O!<%I%&%'%"D>@\<B9TJ}<0 JVM $r%O!<%I%&%'%"2=$7!"Java %P%$%H%3!<%I$rD>@\2r<a!&B9T9kJ}<0G"$k!#;HMQ%a%b%j$,>/J/!"0lHL$K:G$b9bB.G"$k!#

K\O@J8$O%O!<%I%&%'%"D>@\<B9TJ}<0K*1k JVM $N9bB.2=$rL\E*H9$k!#9bB.2=$K$"$?CF$O!"$^$:%9%?%C%/%"!<%-%F%/%A%c$KCmL\$7$?!# JVM GO%9%?%C%/$rD1L$8FG!<%?$N<u$1EO7r9T$&$?$a!"0lHLE*$JRISC %W%m%;%C%5HHfY$F>iD9$J=hM}$,B?$/!"3N3H$,F0E*L?Na$%F%C%W?t$NA}Bg!"$*hS=hM}B.EYDc2<$NMW0xHJCF$$$k!#$=$3$G1i;;$K;HMQ9k%m!<%+%kJQ?t$rJ];}$9$k%1%8%9%?$rMQ0U$7!"$3$N%1%8%9%?$rMQ$$$F%9%?%C%/A`:n$Hl i;;L?Na$H$r$R$H$^$H$a$K$7$F<B9T$9$k!#$3$NJ}K!$O !M?Na>v$_9~$_(**Instruction Folding**)!W$H8F$P$1$F$*$j!"%5%s%^%$%/%m%7%9%F%`%:$NPico-Java $,0lIt:NMQ$7$F$$$k!#<!$K!"%G!<%?0MB8$Khk%Q%$%W%i%s%9%H!<%k$r:o8:9k$?$a$K !VG!<%?Ej5!(**Value Prediction**)!W<jK!rE,MQ9$k!#%G!<%?Ej5!$H$O!"L?Na$N<B9T7k2L$K6I=j@-$,$"$k3H$KCmL\$7!"2a5n$N<B9T7k2L$rMzNrH7$FJ];}$7!"MzNr$K4p$E$-<!2s$N<B9T7k2L$rM=B,$9$k<jK!$G$"$k!#

K\O@J8$O0J2<$Nh&$J9=@.$+$i@.$k!#$^$:Bh2>OK*$$$F Java 2>A[%^%7%s$*$h$S9bB.2=$N8z2L$rD)jNIE*$KB,Dj9k:]$KMQ$$$?%Y%s%A%^!<%/%W%m%0%i%`SPEC-JVM98 $NFCD'$K$D$$$F=RYk!#<!$KBh3>O$K$*$$$F!"SPEC-JVM98 $NM=HwD4::7k2L$rbH$K2>Dj$7$?9bB.Java %W%m%;%C%5$N4pK\9=@.KD$$$F=RYk!#Bh4>OK*$$$FL?Na>v$_9~$_$*$h$S%G!<%?Ej5!$r<BAu9k$?$a$N9=@.$N3HD%KD$$$F=R$Y!"Bh5>O$K$*$$$F8z2L$ND)jNIE*I>2A$r9T$&!#:G8e$KBh6>OK*$$$F7kO@$r=R$Y$k!#

2 Java 2>A[%^%7%s$H SPEC-JVM98 $NFCD'

Java 8@81Kh$j5-=R$5$1$?%=!<%9%3!<%I$r%s%Q%$%k7F@8@.$5$1$k%W%m%0%i%`$O Java %P%$%H%3!<%I$H8F$P$1$k!#Java 2>A[%^%7%s(0J2<JVM) $O Java %P%$%H%3!<%I$r<B9T$9$k2>A[$N7W;;5!$G$"$k!#JVM $OB?$/$N%W%i%C%H%U%)!<%`>e$K%=%U%H%&%'%"Kh$j<BAu$5$1$F$*$j!"3F%W%i%C%H%U%)!<%`>e$G Java %P%$%H%3!<%I$r<B9T$9$k3$H$,2DG=$G$"$k!#3N$?$a Java 8@81$OB?<oB?MM$J%O!<%I/%=%U%H$,@\B3$5$1$F$$$k%M%C%H%o!<%/KHCFA j@-Nh$$8@81G"kH8@$($k!#Java 8@81$,%3%s%Q%$%k$5$1$F@8@.$5$1$k%U%!%$%k$O Java %/%i%9%U%!%$%k$H8FP1!"JVM O3$N%/%i%9%U%!%$%k$N>pJs$rbH$K Java %P%$%H%3!<%I$r<B9T$9$k!#Java %/%i%9%U%!%$%k$O%U%#!<%k%I!"%a%=%C%I$=1>1N>pJsH=1i$,;HMQ$9$kD j?t$r0l3g7F4IM}9k%3%s%9%?%s%H%W!<%k$r4^$s$G$$$k!#%=!<%9%W%m%0%i%`$H%/%i%9%U%!%$%k$N4X78$r?^1 $K<($9!#JVM GO



?^1: Java %/%i%9%U%!%$%k

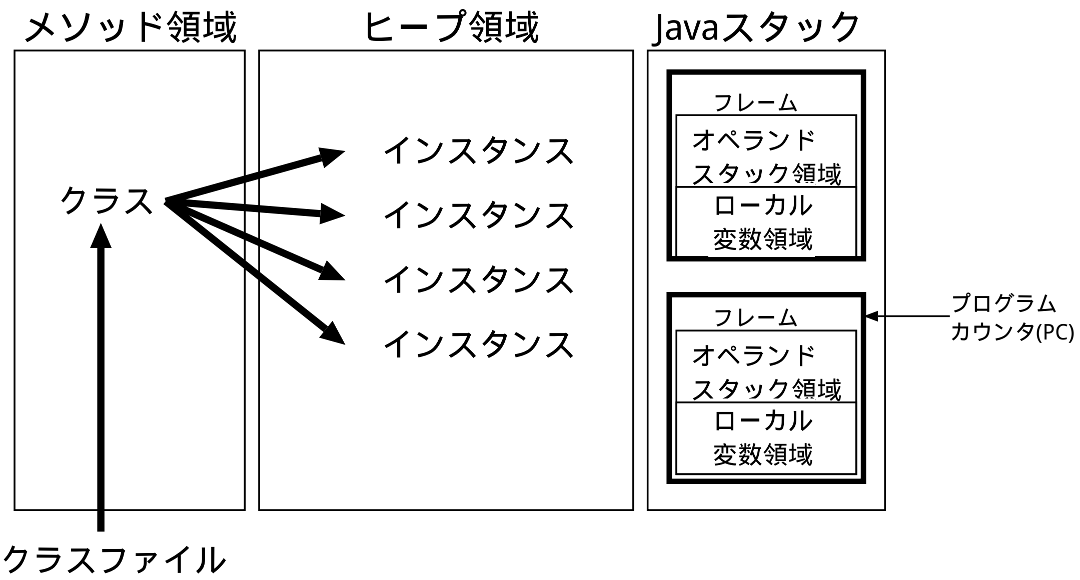
%/%i%9%U%!%$%k$N8zN(2=$r?^$k$?$a$K<B9TCf$K;HMQ9kDj?t$rA4$F$^$HaF%3%s%9%?%s%H%W!<%kCf$G4IM}$9$k!#%3%s%9%?%s%H%W!<%kCf$G3FDj?t$O%(%s%H%jHV9f$rIU1ilF$=$NDj?t$N9=B$$rI=o9%?%0!"Dj?t$ND9$5(%P%$%HD9)!"$=7FDj?t$=$NbN!"$H$$$&7A<0$G3JG<$5lF$$$k!#J8;zNs$r;2>H$9kH$-!"int 7?$NDj?t$r;2>H$9kH$-!"%a%=%C%I$r8F$S=P$9H-!"%U%#!<%k%I$r;2>H$9kH$-!"$3liDj?t$OA4$F%3%s%9%?%s%H%W!<%k$N%(%s%H%jHV9f$r;XDj9k3HG=$NFbMF$rF@$k!#

2.1 Java 2>A[%^%7%s(JVM)

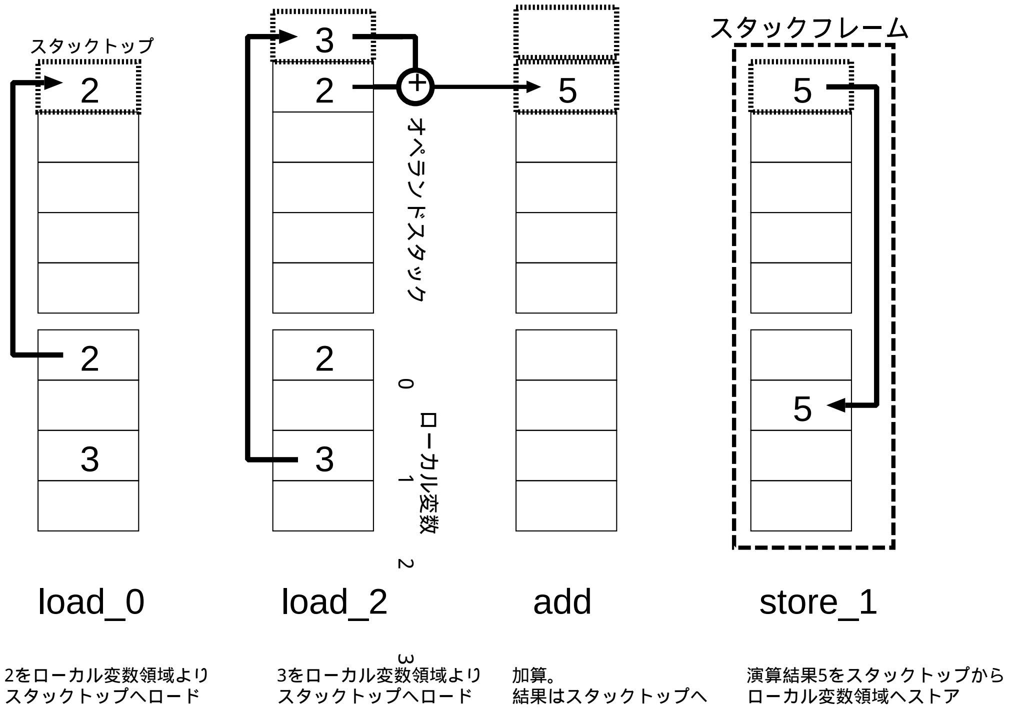
JVM $,;HMQ$9$kNN0h$O?^2$K<($9h&KBg-$/!"%a%=%C%INN0h!"%R!<%WNN0h!"Java %9%?%C%/$+$i9=@.5l$k!#JVM O^$:%/%i%9%U%!%$%krFI_9~sG%a%=%C%INN0h$KE83+9k!#<!$KE83+5l$?%/%i%9%U%!%$%k$K=>CF%$%s%9%?%s%9$r%R!<%WNN0h$K:n@.$7!"%a%=%C%INN0h!"%R!<%WNN0h!"Java %9%?%C%/$r:n6HNN0h$H7F;HMQ7J$,$i%P%$%H%3!<%I$r<B9T9k!#

2.1.1 %l%8%9%?%l%9"!<%-%F%/%A%c

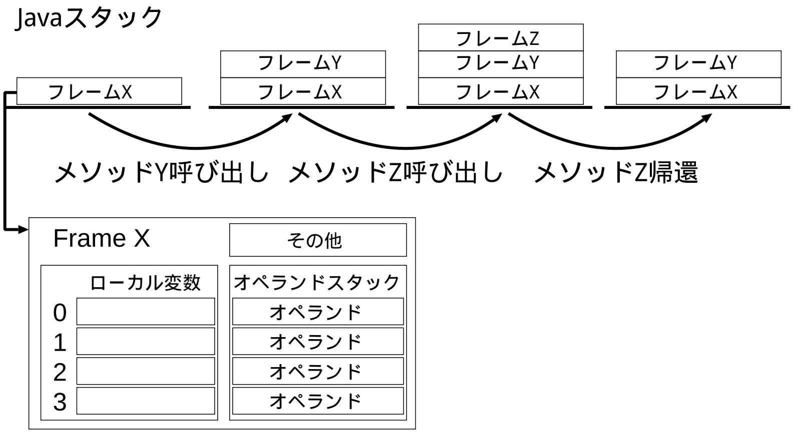
JVM $OMM!9$J%W%i%C%H%[!<%`>e$K$*$$$FEMF0W$K9=C[$G$-$k$h$&!"$=$l$>$l$N%W%i%C%H%U%)!<%`KhCF>r7o$NO[$J$k%l%8%9%?$NMxMQrHr1!"1i;;$r%9%?%C%/>e$G9T$&%9%?%C%/%^%7%s$HJC$F$$$k!#1i;;KI,MWJCM$O%9%?%C%/>e$K push 5l$F$$$kI,MW$,$"$k!#?^3$O2B-93N2C;;$r%9%?%C%/%^%7%s$G9TC?NcG"$k!#JVM $,$"$k%a%=%C%I$r<B9T9kH-$K;HMQ$9$k%9%?%C%/NN0h$r;X7F%9%?%C%/%U%l!<%`$H8F$V!#%a%=%C%I$H$O0lO"$N<jB3$-$r$R$H$^$H$a$K$7$?$b$N;X$7$F$*$j!"C 8@8l$N4X?t$KAjEv$9$k!#JVM $G$O%9%?%C%/%U%l!<%`$,@Q$^lk%9%?%C%/$rJava %9%?%C%/$H$$$&!#1 DN%a%=%C%I$N4IM}$,1 DN%9%?%C%/%U%l!<%`>e$G9T$o$l!"%a%=%C%I$r8F$S=P$7!"La$kEY$KJava %9%?%C%/>e$N%9%?%C%/%U%l!<%`$,:n@./>C5n$5lk!#?^4$K<($9h&$K!"%9%?%C%/%U%l!<%`$O%m!<%+%kJQ?tNN0h!"%*%Z%i%s%I%9%?%C%/NN0h!"<B9T4D6-$r3JG<$9$kNN0h!"$N3 DNNN0h$+$iJk!#%m!<%+%kJQ?tNN0hO=$N%a%=%C%I$,;HMQ9k9YFNJQ?tN?aNNN0h$,3NJ]$5lF$$$k!#%*%Z%i%s%I%9%?%C%/NN0hO=$N%a%=%C%I$N%P%$%H%3!<%IL?Na$,I,MWH9$k:n6HNN0h$G$"$j!"L?NaKI,MWJ%Q%i%a!<%?$dL?Na<B9T8e$N7k2L$,3JG<$5lk!#JVM GO1i;;$O%*%Z%i%s%I%9%?%C%/NN0h$G9Tol$k!#$^$?%a%=%C%I8F$S=P$7;~$N%Q%i%a!<%?$N<u$1EO$7!"$*hS%a%=%C%I5"4T;~NLajCM$N<uEO$7KO%*%Z%i%s%I%9%?%C%/NN0h!"%m!<%+%kJQ?tNN0h$,MxMQ$5lk!#%m!<%+%kJQ?tNN0h$*$h$S%*%Z%i%s%I



?^2: Java 2>A[%^%7%s9=@.



?^3: %9%?%C%/$rMQ$$$?1i;;Nc(2C;;)



?^4: %U%l!<%`$N:n@.$H>C5n

%9%?%C%/NN0h$OJava 8@8l$N%W%m%0%i%`$r%3%s%Q%$%k$9$k;~$KNN0h$NBg$-$5$,7hDj$5$l%9%?%C%/%U%l!<%`NBg-5,<B9TCf$KJQ2=$9k3HO$J$$!#

2.1.2 %R!<%WNN0h

JVM $,07$&%G!<%?7?$O%*%V%8%'%/%H;2>H$*hS%W%j%_%F%#%V7?(char,byte,short,int,long,float,double)$N2<dN`$G$"$k!#$^$?%*%V%8%'%/%H$O%R!<%W>e$KN_3djIU1il$k!#JVM GOG[Ns$b%*%V%8%'%/%H$H7F07ol!"F0E*$K%R!<%W>e$K3NJ]5l$k!#%*%V%8%'%/%H$O%*%V%8%'%/%H:n@.L?NaKhCF?75,$K:n@.$9k3H,G-$k0lJ}!"I,MW$J%*%V%8%'%/%H$rL@<(E*$K2rJ|9kI,MWOJ$$!#JVM GOgarbage collection(gc)$H8F$Plk%W%m%;%9KhCF!";HMQ5l$J$$%*%V%8%'%/%H$O<+F0E*$K3+J|5l$k;EAH$_KJCF$$$k!#

2.2 SPEC-JVM98

K\O@J8GO9bB.2=$N8z2L$rDjNLE*KB,Dj9k?aKJVM $N%Y%s%A%^!<%/%W%m%0%i%`$G$"$kSPEC-JVM98 $rMQ$$$?!#I=1$KSPEC-JVM98 $K4^$^$l$k3F%W%m%0%i%`KD$$$F!"<B9T;~$N%P%$%H%3!<%I$N=P8=IQEY$r<($9!#SPEC-JVM98 KO3F%Y%s%A%^!<%/4H$K-s1!"-s10!"-s100 $N3$D$N<B9T%5%$%:$,MQ0U$5lF$$$k!#s10!"-s100 $OL\0B$H7F-s1 $N10 G\!"100 G\$rI=9,@53N$J?t;z$GOJ$$!#K\8&5fGO5-:\$N$J$$$H$-$O-s100 GB,Djr9T$$!"-s1!"-s10 GB,Djr9TC?H-KO$=$N;]$rI=Cf$K5-$9!#

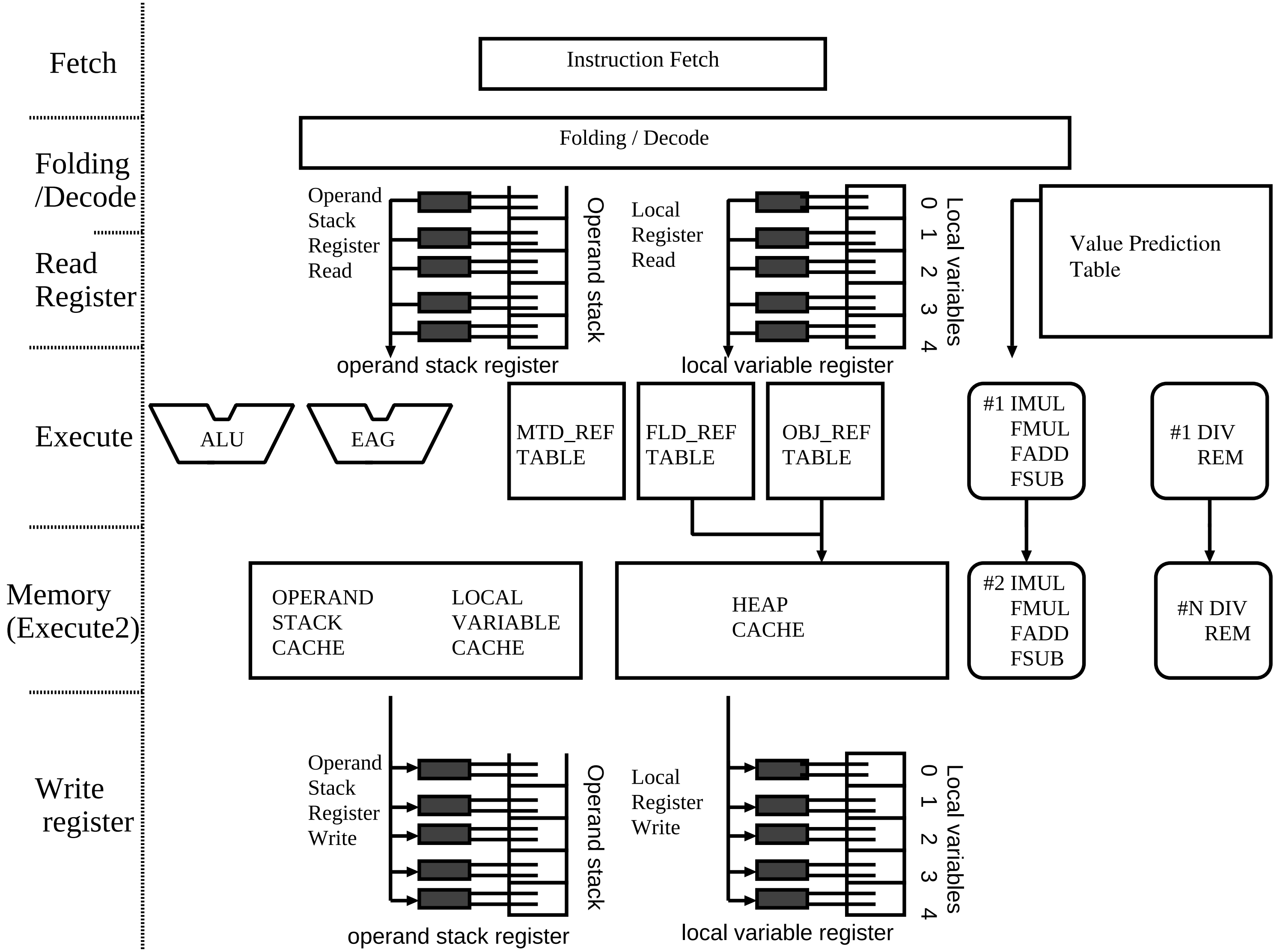
L?Na=P8=IQEY$OL?Na%0%k!<%WKh$K=87W7?bNG"$k!#$3$N7k2L$+$i%m!<%+%kJQ?t%m!<%I$J$IC1=c$JL?Na$@$1GJ$/!"%R!<%W$r;2>H9kL?Na$NIQEY$,9b$$$3H,o+$k!#$^$?%Y%s%A%^!<%/$KhCFO%a%=%C%I8F$S=P$7/5"4TL?Na$,9b$$IQEY$r<($7$F$$$kbNb"$k!#$3N?$aJava %W%m%;%C%5$r9=C[9k$?$aKO%R!<%W;2>H$*$h$S%a%=%C%I8F$S=P7K$D$$$F$b9MN8$7J1lPJi$J$$$H8@$($k!#

3 9bB.Java %W%m%;%C%5$N4pK\9=@.

K\>OGOSPEC-JVM98 $NM=HwD4::$N7k2LrbHK!"5CJ%Q%$%W%i%$%s$+$i9=@.5l$k%W%m%;%C%5$N4pK\9=@.$r2>Dj$9$k!#

3.1 %Q%$%W%i%$%s9=@.

?^5$KK\O@J8$K$*$$$F2>Dj7?%W%m%;%C%59=@.$r<($9!#%Q%$%W%i%$%s$O Fetch - Folding/Decode - Execute - Memory - Write $N5CJ9=@.$H9k!#3F%9%F!<%8K*1kF0:n$r0J2<$K<($9!#



?^5: Java %W%m%;%C%5$N4pK\9=@.

I=1: SPEC-JVM98 K*1kJava %P%$%H%3!<%I<B9T;~$NL?Na=P8=IQEY

	compress	jess	db	javac	mpegaudio	mtrt
%m!<%+%kJQ?thj%m!<%I	32.5%	37.3%	40.6%	35.4%	32.8%	33.4%
%m!<%+%kJQ?tXN%9%H%"	9.1%	5.4%	6.9%	4.5%	6.3%	1.7%
%R!<%Whj%m!<%I	19.4%	18.3%	23.3%	16.5%	20.5%	17.2%
%R!<%WXN%9%H%"	4.7%	1.6%	1.1%	4.5%	3.3%	2.4%
1i;;(8GDj>.?tE@!"IbF0>.?tE@)	9.6%	1.3%	5.9%	4.3%	14.3%	7.0%
J,4t	6.1%	10.7%	8.1%	8.3%	3.3%	3.6%
%a%=%C%I8F$S=P$7/5"4T	3.6%	12.8%	7.0%	13.3%	1.9%	26.2%
Dj?t$N%W%C%7%e	7.1%	5.6%	1.3%	5.3%	12.8%	5.8%
$=$NB>$N%9%?%C%/A':n	7.3%	2.2%	2.6%	3.6%	4.0%	1.7%
?75,%*%V%8%'%/%H:n@.	0.0%	0.4%	0.2%	0.3%	0.0%	0.3%
$=$NB>	0.4%	4.4%	3.0%	4.0%	1.0%	0.5%

Fetch L?Na%U%'%C%A!#L?Na$N@h9T<hF@$r9T$&!#

Folding/Decode Read Register L?Na$N%G%3!<%I$*hS8e=R9kL?Na>v$_9~$_$r9T$$!"I,MW$J%1%8%9%?$rFI$_=P$9!#

Execute 1i;;%9%F!<%8!#1i;;!"%"%I%l%97W;;!"$*$h$S3FJQ4{9I=$r;2>H9k!#ALU(1i;;4o)$O!"F~NO64 %S%C%H!_2!"=PNO64 %S%C%HH7!"Java $Nlong 7?(64 %S%C%H) $N1i;;$K$b1 %5%$%/%k$GBP1~$G$-$kbNH9$k!#1i;;$KMW9k%5%$%/%k?t$O0J2<$r2>Dj$7$?!#

1 %5%$%/%k(Execute %9%F!<%8$N$_)$G1i;;$,40N;8GDj>.?tE@2C8:;;

2 %5%$%/%k(Execute %9%F!<%8$HMemory %9%F!<%8) $G1i;;$,40N;8GDj>.?tE@>h;;!"IbF0>.?tE@2C8:>h;;!"7?JQ49

$=$l0J>e$N%5%$%/%k?trI,MWH9k1i;;8GDj>.?tE@=|;;!"IbF0>.?tE@=|;;

Memory %R!<%W/%*%Z%i%s%I%9%?%C%//%m!<%+%kJQ?tN?aN3F%-%c%C%7%e$r;2>H$9$k!#$?$@$78e=R9kh&$K1i;;$K2 %5%$%/%k0J>eMW$9$kL?Na$K$D$$$F$O Memory %9%F!<%8$K$*$$$F$b1i;;$r9T$&!#

Write Register 8e=R9k%*%Z%i%s%I%9%?%C%/%1%8%9%?5Z$S%m!<%+%kJQ?t%1%8%9%?$X$N=q$-9~$_$r9T$&!#

3.2 %R!<%W;2>H$*$h$S%a%=%C%I8F$S=P$79bB.2=$N$?$a$NJQ49I=

%R!<%W%"%/%;%9!"$*$h$S%a%=%C%I8F$S=P7N:]$N%"%I%l%9JQ49%$r9bB.2=9k$?$a$K3 DNJQ49I=$r2>Dj7?!#$3li$NJQ49I=$O9bB.$J%a%b%j$Khj9=@.5l$k!#

%*%V%8%'%/%H;2>HJQ49I= **(OBJ_REF TABLE)**

%*%V%8%'%/%H;2>HJQ49I=$O%*%V%8%'%/%H$r;2>H9k:]KI,MWHJk@hF,%"%I%l%9$N<hF@$r9bB.2=9k!#%*%V%8%'%/%H;2>HNCMGJQ49I=$r0z$-!"%R%C%H9l$P<B%"%I%l%9$r9bB.$K<hF@$G$-$k!#%_%9$7$?>l9g$O%*%V%8%'%/%H;2>H$rbH$K%"%I%l%97W;;$r9T$$G$F<B%"%I%l%9$r<hF@9k!#0J2<$K%*%V%8%'%/%H;2>HJQ49I=$rMxMQ9kL?Na0lMw$r<($9!#

%U%#!<%k%I;2>HJQ49I= **(FLD_REF TABLE)**

%*%V%8%'%/%H$N%U%#!<%k%I$N;2>H$r9bB.2=$9k?aNJQ49I=G"$k!#JVM GCF0E*$K%*%V%8%'%/%H$r%j%s%/9kKN$G%U%#!<%k%I$N%*%U%;%C%HCM$O>o$KF0E*$K7hDj$5lk!#%U%#!<%k%I$r;2>H9k:]$O!"L?Na$G;XDj7?%3%s%9%?%s%H%W!<%kXN%$%s%G%C%/%9$r%-!<$H7F%3%s%9%?%s%H%W!<%k$r;2>H$7!"%*%U%;%C%HCM$rF@$k!#%*%U%;%C%HCM$rF@k^$G7+jJV7%/%i%9$r;2>H$9kN$G%*%U%;%C%HCM$N<hF@KOB?$/$N3%9%HrMW9$k!#$=3G%*%U%;%C%HCM<hF@$r9bB.2=$9k?aK%U%#!<%k%I;2>HJQ49I=$rMQ0U$7!"L?NaKh$j;XDj$5l?%3%s%9%?%s%H%W!<%k$N%$%s%G%C%/%9$rMQ$$$FJQ49I=$r0z$-!"%R%C%H9l$PD>@\%*%U%;%C%HCM$r<hF@9k!#%_%9$7$?>l9g$O%/%i%9$r;2>H$7%*%U%;%C%HCM$r<hF@9k!#

invokevirtual,invokespecial,invokeinterface,iaload,daload,baload
caload,saload,faload,laload,iastore,dastore,bastore,castore,fastore
lastore,getfield,putfield,arraylength,instanceof,checkcast

getfield,putfield,getstatic,putstatic

0J2<$K%U%#!<%k%I;2>HJQ4 9I=$rMxMQ9kL?Na0l Mw$r<($9!#

%a%=%C%I;2>HJQ4 9I=(**MTD_REF TABLE**) %a%=%C%I8F$S=P$7$r9bB.2=$9k?aNJQ4 9I=G"$k!#JVM GOF0E*$K%a%=%C%I$r%j%s%/9k$?aK!"%a%=%C%I8F$S=P$7L?Na$,<B9T5lkEYKL?Na$G;XDj7?%a%=%C%I$N@hF,%"%I%l%9$r%/%i%9$N%a%=%C%INCf+$i8+D+k^$GC5$9!#=>CF%a%=%C%I8F$S=P7KBg$-$J%3%9%HrMW9$k!#%j%s%/r?Ik<j4V$r>J$-9bB.2=$r?^k?aK%a%=%C%I;2>HJQ4 9I=$rMQ0U$9$k!#%a%=%C%I;2>HJQ4 9I=$G$OL?Na$G;XDj7?%3%s%9%?%s%H%W!<%kXN%$%s%G%C%/%9$rMQ$$$FJQ4 9I=$r0z$-!"%R%C%H9l$P%a%=%C%I$N@hF,%"%I%l%9$rF@$k!#%_%9$N>l9g$O%a%=%C%INCf+$iL\E*$N@hF,%"%I%l%9$rC5$9!#0J2<$K%a%=%C%I;2>HJQ4 9I=$rMxMQ9kL?Na0lMw$r<($9!#

3.3 JQ4 9I=$NM-8z@-

5F!"3 DNJQ4 9I=$r9=@.$9kK$"$?CF!"$=$l$>$l$K:GE,$J% (%s%H% j?t!"%&%'%$?t$r8!F$$9k?aND4::$r9T$C$?!#JVM G"$kKaffe $*$h$S SPEC-JVM98 $rMQ$$!"3F%Y%s%A%^!<%/K*1kJQ4 9I=XNF~NO%-!<$NJ,I[$rD4::7?!#3FJQ4 9I=KD$$$F!";2>H$NI QEY!";2>H$N<cN`rB,Dj7$?!#7k2L$rI=2!AI=4$K<($9!#3N7k2Lhj!"%U%#!<%k%I$d%a%=%C%I$K4X7FI,MW$J% (%s%H% j?t$O>/J/!"3l$iF s$D$N;2>HJQ4 9I=$O9b!9300 % (%s%H% j$"$l$P100%$N%R%C%HN($,F@$ilk$H8@$($k!#0lJ}!"%*%V%8%'%/%H;2>HJQ4 9I=$K4X$7FO!"6KaFB?$/$N% (%s%H% j?trI,MWH9k3H$,$o$+$k!#

I,MW% (%s%H% j?t$NB,Dj7k2L$rbH$K!"%*%V%8%'%/%H;2>HJQ4 9I=$r<B:]$K9=@.$7!"%R%C%HN($rB,Dj7?!#%*%V%8%'%/%H;2>HJQ4 9I=$N% (%s%H% j?t$O256!"512!"1024!"%&%'%$?t$O1!"2!"4 H7$?!#%*%V%8%'%/%H;2>H$K$OKaffe FbIt$G;HMQ5l$F$$$kCMr=N^$^;HMQ$7!"% (%s%H% j?t$,256 NH$-$O%*%V%8%'%/%H;2>H$N2<0L8 %S%C%H!"512 NH$-$O2<0L9 %S%C%H!"1024 NH$-$O2<0L10 %S%C%H$rMQ$$$FJQ4 9I=$r0z$/$H2>Dj$7$?!#3F!9$N%Y%s%A%^!<%/GB,Dj77k2L$NJ?6Q$rHC$?$bNrI=5$K<($9!#7k2L$K<($5l?h&$K!"0lHLE*$J RISC %W%m%;%C%5K*1k TLB $G4|BT$5lkh&$J 100% $K6a$$%R%C%HN($OF@$k3H$,$G$-$J$+$C$?!#$3N?$a!"%*%V%8%'%/%H;2>HJQ 9 9I=KD$$$F$O%_%9%Z%J%k%F%#$rL5;k9k3H$,$G$-$J$$$H8@$($k!#

3.4 %*%Z%i%s%I%9%?%C%/!"%m!<%+%kJQ?t!"%R!<%W$N;2>H9bB.2=$N$?$a$N%-%&%C%7%e5!9=

<!$K%9%?%C%/!"%R!<%W$+iNCMNFI_=q$-$N9bB.2=$r?^$k$?$a$N%-%&%C%7%e$K$D$$$F!"$=$NM-8z@-$rD4::$7$?!#

3.4.1 %*%Z%i%s%I%9%?%C%/$*$h$S%m!<%+%kJQ?t%-%&%C%7%e

L?NaIQEY$ND4::7k2L$h$j%m!<%+%kJQ?tNN0h$*hS%*%Z%i%s%I%9%?%C%/NN0hXN%"%/%;%9$OA4L?NaCf9b$$3d9g$r@j$a$F$$$k3H$,H=L@$7$?!#$=3G%*%Z%i%s%I%9%?%C%/NN0h!"%m!<%+%kJQ?tNN0h$r%-%&%C%7%s%0$7$F%"%/%;%9$N9bB.2=$r?^$kI,MW$,$"$k!#%*%Z%i%s%I%9%?%C%/NN0h!"%m!<%+%kJQ?tNN0h$r%-%&%C%7%e$XE83+7?>l9g!'$"$k%a%=%C%I$,;2>H$9kNO=$N%U%l!<%`Fb$@1G$"$k3H+$i%R%C%HN($O9b$/$J$j!"%-%&%C%7%e$N%5%$%:$O>.5/Fh$$$3H,M=A[5l$k!#%9%H%"

invokevirtual,invokespecial,invokestatic,invokeinterface

I=2: MTD_REF Table

benchmark	;2>H2s?t	%(%s%H%j?t
compress	2,2598,7533	212
jess	1,2677,2337	229
db	1,3922,0030	220
javac	1,8783,1283	274
mpegaudio	1,0967,4801	233
mtrt	2,8752,8186	222

I=3: FLD_REF Table

%Y%s%A%^!<%/	;2>H2s?t	%(%s%H%j?t
compress	23,6468,8170	148
jess	2,9265,0375	171
db	6,8373,4501	149
javac	4,6929,6250	235
mpegaudio	10,9955,1263	247
mtrt	3,4775,3519	153

I=4: OBJ_REF Table

benchmark	;2>H2s?t	%(%s%H%j?t
compress	32,0777,7272	2896
jess	5553,37047	18,7876
db -s10	1988,0207	13,4928
javac -s10	2068,1478	9,4487
mpegaudio	26,8894,8000	4565
mtrt -s10	7398,6591	503672

I=5: %*%V%8%'%/%H;2>HJQ49I=%R%C%HN(!#s1 $GB,Dj!#C10L(%)

	%&%'%$?t		
%(%s%H%j?t	1	2	4
256	79.08	86.95	91.03
512	79.37	87.33	91.52
1024	83.19	90.18	93.67

I=6: Java %9%?%C%/%-%&%C%7%e%R%C%HN(

benchmark	Am;2>H2s?t	1 %-%m%P%$%H;~%R%C%HN(	16 %-%m%P%$%H;~%R%C%HN(
compress	40,5350,6528	100.0%	100.0%
jess	7,3208,6898	99.99%	100.0%
db	16,0874,1140	100.0%	100.0%
javac	9,2352,7376	99.99%	100.0%
mpegaudio	3,76390,4234	100.0%	100.0%
mtrt	7,2026,6676	100.0%	100.0%

%P%C%U%!$r2>Dj$7$F%*%Z%i%s%I%9%?%C%/$*hS%m!<%+%kJQ?t%-%&%C%7%eXN%i%$%H$O%Q%$%W%i%$%s$,%9%H!<%k$7$J$$$H$N>r7o$G!"%*%Z%i%s%I%9%?%C%/$*$h$S%m!<%+%kJQ?tFI$_=P$7L?Na$K$D$$$F1%i%$%s64%P%$%H!"%(%s%H%j?t16(%-%&%C%7%e%MFNL1%-%m%P%$%H;~)$*hS256(16%-%m%P%$%H;~)!"%&%'%$?t1$N%@%$%1%/%H%^%C%T%s%0J}<0$H2>Dj$7FB,Dj7$?7k2L$rI=6$K<($9!#

3.4.2 %R!<%W%-%&%C%7%e

<!$K%R!<%W%-%&%C%7%e$R%C%HN($r%7%_%e%l!<%7%g%s$KhjB,Dj7?!#%R!<%WXN%"%/%;%9$O%*%V%8%'%/%H;2>HI=$Khj%*%V%8%'%/%H$N@hF,%"%I%l%9$r<hF@$7!"%U%#!<%k%I;2>HJQ49I=$h$j<hF@$7$?%*%U%;%C%HCM$r2C$($k3H$G9T$&!#%R!<%W$O%*%Z%i%s%I%9%?%C%/NN0h!"%m!<%+%kJQ?tNN0hNh$&$K;2>HHO0O$,8BDj$5lF$*$i$:!"%R!<%WCf$r<+M3$K%"%/%;%9$9k3H,G-$k!#Kaffe$,FbIt$G;HMQ$9$k%*%V%8%'%/%H;2>H$r%*%V%8%'%/%H@hF,%"%I%l%9H_J7!"%*%V%8%'%/%H;2>H$r%-!<$H9k!#1%i%$%s64%P%$%H(16%o!<%I)$N%@%$%1%/%H%^%C%T%s%0J}<0(%&%'%$?t1)$N%-%&%C%7%e9=@.$r2>Dj$7$R%C%HN($rB,Dj7?!#%(%s%H%j?t$O256(%-%&%C%7%e%MFNL16%-%m%P%$%H)!"1024(%-%&%C%7%e%MFNL64%-%m%P%$%H)$N2<oN`$r2>Dj$7$?!#D4:::$NBP>]H7$?L?Na$rI=7$K!"B,Dj7k2L$rI=8$K<($9!#B,Dj7k2Lhj!"%R!<%W%-%&%C%7%el6%-%m%P%$%H;~$NJ?6Q%R%C%HN($O86.5%!"64%-%m%P%$%H;~$O91.2%$G$"$C$?!#%R!<%W%-%&%C%7%e$K$D$$$F$b!"%_%9%Z%J%k%F%#$rL5;k9k3HOG$-$J$$$H$$$($k!#

0J>e3DNJQ49I=$*$h$S2$D$N%-%&%C%7%e$ND4::7k2L$rAm9g$9kH!"%a%=%C%I;2>HI=!"%U%#!<%k%I;2>HI=$*$h$S%*%Z%i%s%I%9%?%C%/%-%&%C%7%e!"%m!<%+%kJQ?t%-%&%C%C%7%e$K$$$D$$$F$OJQ49%_%9;~!"%-%&%C%7%e%_%9%R%C%H;~$N%Z%J%k%F%#$rL5;k9k3HG-kbNN%*%V%8%'%/%H;2>HJQ49I=$*$h$S%R!<%W%-%&%C%7%e$K$D$$$F$O%_%9;~$N%Z%J%k%F%#$,L5;k$G$-$J$$$H8@$($k!#

4 L?Na>v$_9~$_$*$h$S%G!<%?Ej5!$N$?$a$N3HD%

4.1 L?Na>v$_9~$_$N86M}

%9%?%C%/%"!<%-%F%/%A%c$NJVM$,bD<eE@G"$k!"%"%/%;%9$NHs8zN(@-$r2r>C$9Y/!"FCDj$NL?Na$N<B9TA08e$K9T$olkDj7?E*$J%9%?%C%/$X$Npush / pop A`:n$rA0=R7?%l%8%9%?$rMQ$$$FGS=|7h$&$H$$$&9M$(J}$,L?Na>v$_9~$_(Insturction Folding)G"$k!#$3lO%9%?%C%/%"!<%-%F%/%A%c$,%9%?%C%/%H%C%W$X$N%"%/%;%9$7$+5v2D$7$J$$$?aG$"$j!"L?Na<B9T;~$N@-G=Dc2<$N860xHJCF$$$k!#3Nh&$JE57?E*$JNc$Oli;;L?NaA08e$K$"$iol$k!#JVM$Oli;;L?Na$r<B9T$9kH$-F~NO$K%9%?%C%/%H%C%WNCMrMQ$$!"li;;$4CN;8e,7k2L$r%9%?%C%/%H%C%W$K=PNO$9$k!#?^6:8$Kli;;NNcr<($9!#Dj?t!"%m!<%+%kJQ?t$N%9%?%C%/%H%C%WXN%m!<%I$,li;;A0$K!"$=$7$Fli;;=*N;8e$K7k2L$,li;;7k2L$,3JG<5l$F$$$k%9%?%C%/%H%C%WNCMr%m!<%+%kJQ?t$K%9%H%"$9k3H,6KaFIQHK$K9T$olk!#>r7oJ,4tL?Na!"%R!<%WA`:nL?Na$J$I$K$*$$$F$bF1MM$NDj7?E*$J:n6H$,$=$NL?Na$NA08e$K7+$jJV$5$l$k$3$H$,B?$$!#$3$N$h$&$JDj7?E*$JL?Na$Hli;;L?Na!">r7oJ,4tL?Na!"%R!<%WA`:nL?Na!"JI$r%R$H$^$HaK$F!"l%U%m!<%G<B9T$7h&$H$$$&9M$(J}$,L?Na>v$_9~$_G"$k!#M>J,$J%9%F%C%W$r:o=|$9k3HKhk<B9TB.EY$N8~>e$,8+9~$^$l$k!#

4.2 L?Na>v$_9~$_$N<BAu

JVM$N;EMM$KOJ$$$FH<+$N%l%8%9%?$rMQ0U9k!#3liN%l%8%9%?$O%*%Z%i%s%I%9%?%C%/$c%m!<%+%kJQ?t$N0lIt$rJ];}$7!"<g5-21$c%-%&%C%7%ehj$b9bB.$K%G!<%?cjHj9k!#%l%8%9%?$r;HMQ$9$kL?Na$O<g5-21$c%-%&%C%7%e$K%"%/%;%9$9$kI,MW$,$J$$!#3N%l%8%9%?KhCF<g5-21$c%-%&%C%7%e$X$N%"%/%;%9$,8:k3H+$i<B9T%5%$%/%k?t$,:o8:$5lk!#5iK3$N%l%8%9%?$rMQ$$$FL?Na>v$_9~$_$r<B8=$7!"JVM$N9bB.2=$r7W$k!#

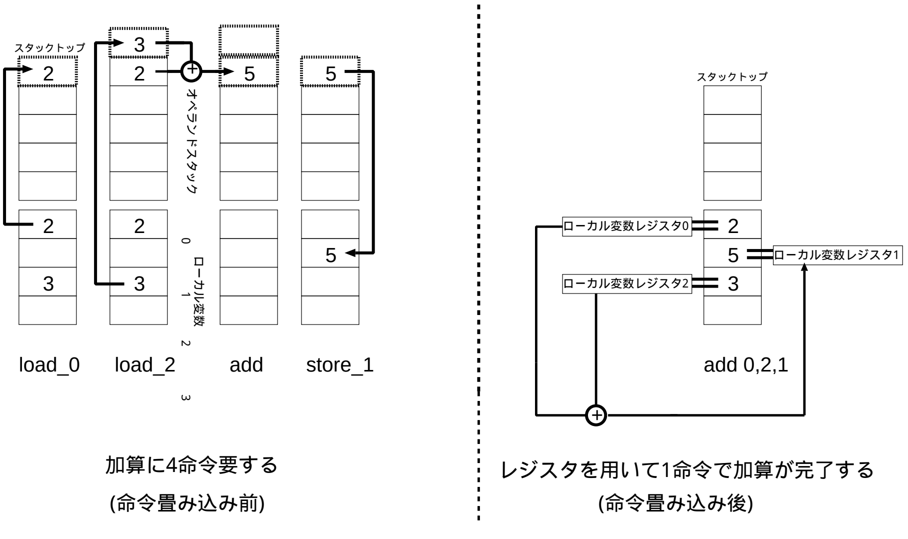
FH<+IU2C%l%8%9%?0lMw

I=7: %R!<%W%"%/%;%9L?Na

iaload,daload,baload,caload,saload,faload,laload
iastore,dastore,bastore,castore,sastore,fastore,lastore
getfield,putfield,arraylength,instanceof,checkcast

I=8: %R!<%W%-%&%C%7%e%7%_%e%1!<%7%g%sB,Dj7k2L!#%R%C%HN(C10L(%)

1 %i%$%s16 %o!<%I,256 %(%s%H%j(64k %P%$%H),64 %(%s%H%j(16k %P%$%H)					
benchmark	Am;2>H?t	%R%C%H?t(16k %P%$%H)	%R%C%HN(	%R%C%H?t(64k %P%$%H)	%R%C%HN(
compress	32,0778,4265	2,8152,9509	87.8	30,7633,8058	95.9
jess	5,6086,3532	4,8137,2914	85.8	5,1098,2140	91.1
db	11,8343,5852	9,4484,2994	79.2	9,8046,6755	82.8
javac	7,1354,9215	5,4923,0426	88.0	6,5571,8666	91.9
mpegaudio	26,9027,4157	21,6386,3580	95.1	26,0831,8958	97.0
mtrt	7,2251,7473	5,6398,1899	82.8	6,3915,5468	88.5
J?6Q	—	—	86.5	—	91.2



?^6: L?Na>v$_9~$_$NNc

- %3%s%9%?%s%H%1%8%9%?!2 % (%s%H%j(L?NaCf$N Dj?t$rJ]; }9k! #)

- %*%Z%i%s%I%9%?%C%/%1%8%9%?!1'2 % (%s%H%j(<B9T Cf$N%a%=%C%I$,; HMQ9k%*%Z%i%s%I%9%?%C%/NN0h$N%9%?%C%/%H%C%W$+$i12 % (%s%H%j J,$rJ]; }9k! #)

- %m!<%+%kJQ?t%1%8%9%?!4!"8!"16!"!g(<B9TCf$N%a%=%C%I$,; HMQ9k%m!<%+%kJQ?tNN0h$N HV9f$N<c$$=gHV$+$i?t% (%s%H%jJ,$rJ]; }$9$k! #K\8&5f$GO3$N%1%8%9%?$N?t$r4!"8!"16!"!g$HJQ2=5;$FL?Na>v$_9~$_$N8z2L$N JQ2=$rD4: :9k! #)

K\%W%m%;%C%5GOFetch %9%F!<%8KF@h9TL?Na$r==J,$K<hF@$7!"Folding/Decode %9%F!<%8KFL?Na>v$_9~$_$r9T$&! #L?Na>v$_9~$_$,2DG=$HJk>r7o$OD j7?E*$J: n6H$K; HMQ$5$1$k%G!<%?$, A0=R$7$?%3%s%9%?%s%H%1%8%9%?$b7/$O%m!<%+%kJQ?t%1%8%9%?$KJ]; }$5$1$F$$$k3HG"$k! #?^61&$K<(9h$&$KK\Mh$J$i$P%9%?%C%/%H%C%W$X%m!<%I$5$1F+$i1i; ;$,; O$^$j!"1i; ;7k2L$r%9%?%C%/%H%C%W$+$i%m!<%+%kJQ?t$X$H%9%H%"$7$F$$$?N,%1%8%9%?$rMQ$$$k3H$G1i; ;A08e$N%m!<%I/%9%H%"$r>JN,$7!"A08e$NL?Na$b013g7F1i; ;$r40N;$9k3H,G-$k! #

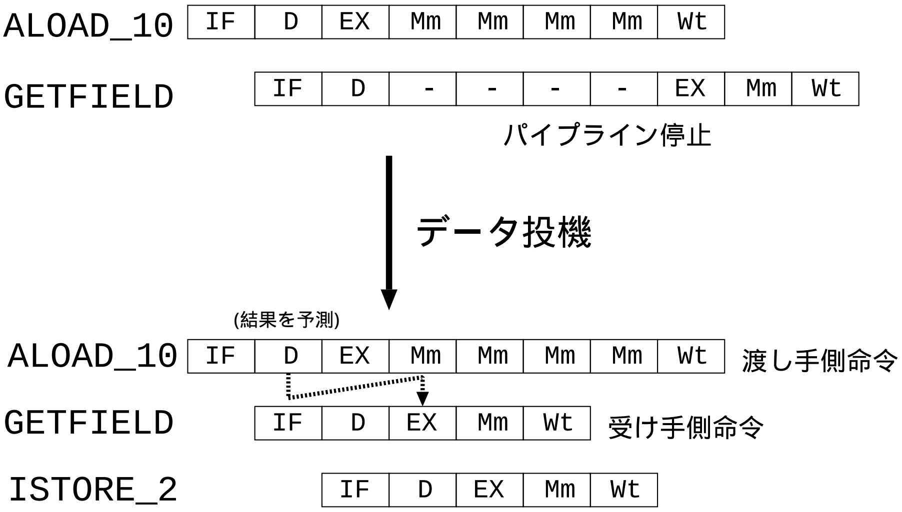
4.3 %G!<%?Ej5!$N86M}

%G!<%?Ej5!(Value Prediction) $O!"9M$(J}$rJ,4tM=B,!Ej5!E*<B9T$HF1$8$/$7!"CM$N6I=j@-(Value Locality) $rMxMQ$7$FL?Na$N<B9T7k2L$rM=B,$7h&H9$k<jK!$G$"$k! #%G!<%?Ej5!$N4QE@$+$i8@$($P!"J,4tM=B,$O0 $+1 $rM=B,$7$F$$$k$H9M$(i1$k! #J,4tM=B,$H$N0c$$$O!"J,4tM=B,$O0 $+1 $NFs<cN`$NIAi+NCMrM=B,7F$$$kNKBP7F%G!<%?M=B,$O0 $+$i$2^w (w $O%W%m%;%C%5$Khj0 [Jk) $NHC00O$GCM$rM=B,$7J/FOJi$J$$! #3N; v<B$+$i!"J,4tM=B,$HHf3S$7$F%G!<%?M=B,$OM=B,$rE*Cf$5$;$k3H$,:$FqJNGO$J$$$+$H; W$o1k! #7+$7D4: :$N7k2L!"JVM K*$$$FbCMN6I=j@-Kh$j!"$$$/D+$NL?Na$K$*$$$F$O==J,$JM=B,E*CfN($,F@$i1k3H$,$o$+$C$?! #?^4.3$K%G!<%?Ej5!NNcr<($9! #

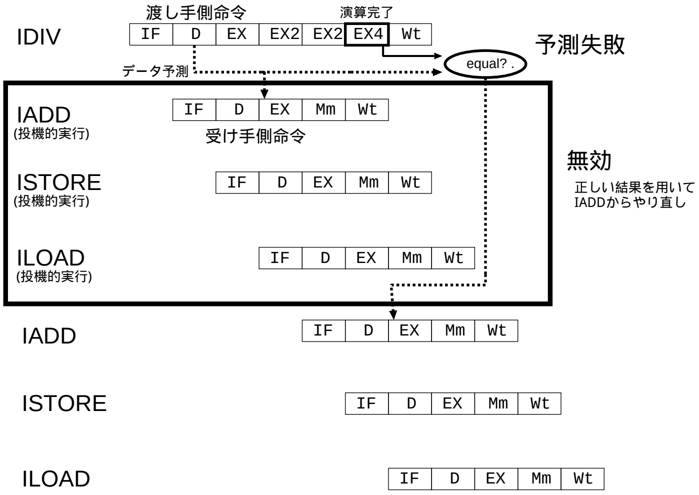
4.4 %G!<%?Ej5!5!9=$N<BAu

K\8&5fGO%G!<%?Ej5!$rMQ$$$F1i; ;7k2L!"%a%b%j%m!<%I7k2L$r3JG<$9$k%*%Z%i%s%I%9%?%C%/$N%9%?%C%/%H%C%W$K=q$-3^1kCM$rM=B,$9$k! #%9%?%C%/%H%C%WCM$rM=B,$78eB3L?Na$NEj5!E*<B9T$r9T$&3HKh$j!"%G!<%?0MB8$Khk%Q%$%W%i%$%s$N%9%H!<%k$r2sHr9k3H$,4 |BT$G$-$k! #$3$3GO%G!<%?0MB8L?Na$r<u$1<jB&L?Na!"H%G!<%?0MB8L?NarEO7<jB&L?Na$H8F$V! #%G!<%?M=B,$r9T$&KOCM$N6I=j@-$rMxMQ9k$?$a$K2a5n$NMzNr$rJ]B8$9$k%F!<%V%k$,I,MWG"$j!"J,4tM=B,$hjbBg$-$J%F!<%V%k$r%W%m%;%C%5$KMQ0U9kI,MW$,$"$k! #%F!<%V%k$X$NF~NO$O%W%m%;%C%5$N>uBV(%W%m%0%i%`%+%&%s%?!"%$%s%9%H%i%/%7%g%s%U%#!<%k%I)!"=PNO$O<u$1<jB&L?NaKEO9M=B,CMHJ$j!"M=B,CM$rbiC?<u$1<jB&L?Na$O$=$NM=B,CM$rMQ$$$FExecute %9%F!<%8$+$iEj5!E*$KL?Na$r<B9T9k! #1i; ;L?Na$N>19g!"M=B,$5$1$?CMOEO7<jB&L?Na$N1i; ;$N=*N;D>8e$K!"$D$^$jEO$7<jB&L?Na$NExecute %9%F!<%8$N=*N;D>A0$K@5<0$J7k2L$H$NHf3S$,9To1!"$=$NCM$,@5$7$1$1$PEj5!E*<B9T$O@.8yHJj=N^$^L?Na$r7QB3$9$k3H$,$G$-$k! #0lJ}!"CM$,Ey$7$/$J$$>19g$OM=B,$,<:GT7?H-G"$j!"$=$N>19g$OEj5!E*$K<B9T$5$1$?L?Na$rA4$FL58zH7!"@5<0$J7k2L$rMQ$$$F<u$1<j$NL?Na$NExecute %9%F!<%8$+$i<B9T$rdjJ*$9! #?^4.4$K%G!<%?Ej5!$,<:GT$7$?Nc$r<($9! #-%&%C%7%e!&%g5-21%"%/%;%9L?Na$N>19g$K$O@5<0$J7k2L$rF@$kMemory %9%F!<%8$N=*N;D>A0$K$*$$$FM=B,CMHNHf3S$r9T$$!"@5$7$1$1$PEj5!E*<B9T$O@.8y$7$=$N$^$^7QB3$7$F<B9T$rB3$1!"4V0c$$$G$"$1Pb$&0lEY@5<0$J7k2L$rMQ$$$F<u$1<jL?Na$NExecute %9%F!<%8$+$i<B9TrdjJ$*$9! #%G!<%?M=B,$,@5$7$/$J$$$H$-$N%Z%J%k%F%#%5%$%/%k$K$D$$$F$OK\8&5f$K$*$$$F$O0 $H2>Dj$7$?! #?^4.4$K<(9h$&$K!"MzNr$K4p$E$/%G!<%?M=B,$K$O<!$Nh&$JJ}K!$,9MO F$5$1$F$$$k! #

Last Value Prediction :G?7NCMN$_$rTable $KJ]; }$7(MzNr1) <!2s$N<B9T; ~!"$=NCMrM=B,CMH7F=N^$^MQ$$$k<jK!! #



?^7: %G!<%?Ej5!$NNc



?^8: %G!<%?Ej5!<:GT$NNc

Stride Value Prediction Last Value Prediction Nh$&$KA02s;HMQ$5$1$?CM$r$=$N$^$^M=B,CMH9kNGOJ/!"A0!92sNCMHA02sNCMN:9(Stride) $KCmL\$7!"M=B,r9$k<jK!!#Last Value Prediction $OStride Value Prediction $NFCJL$J>l9g(Stride = 0) $H9M$(k3H,G-$k!#0lDj$NI}$GA}2C$9$k%k!<%W9=B$;~$NM=B,$KE,7F$*$j!"Last Value Prediction hj$b9b$$M=B,E*CfN($rF@$k3H$,$G$-$k!#

Context Value Prediction 2a5n?t2sJ,$NMzNr$rJ];}$7!"M=B,$r9k<jK!!#%a%b%j$NFbMF$J$I!"Stride Value Prediction $,$"$^$jDIMQ7J$$$h$&$J>u67K*$$$F$bM=B,$,2DG=$GLast Value Prediction(MzNr1 2s) hj$bM=B,E*CfN($,9b$$!#

K\8&5fGO4JC1N?aK Last Value Prediction(LVP) $rMQ$$$?I>2A$r9T$&3HK7$?!#

5 9bB.2=<jK!$NDjNIE*I>2A

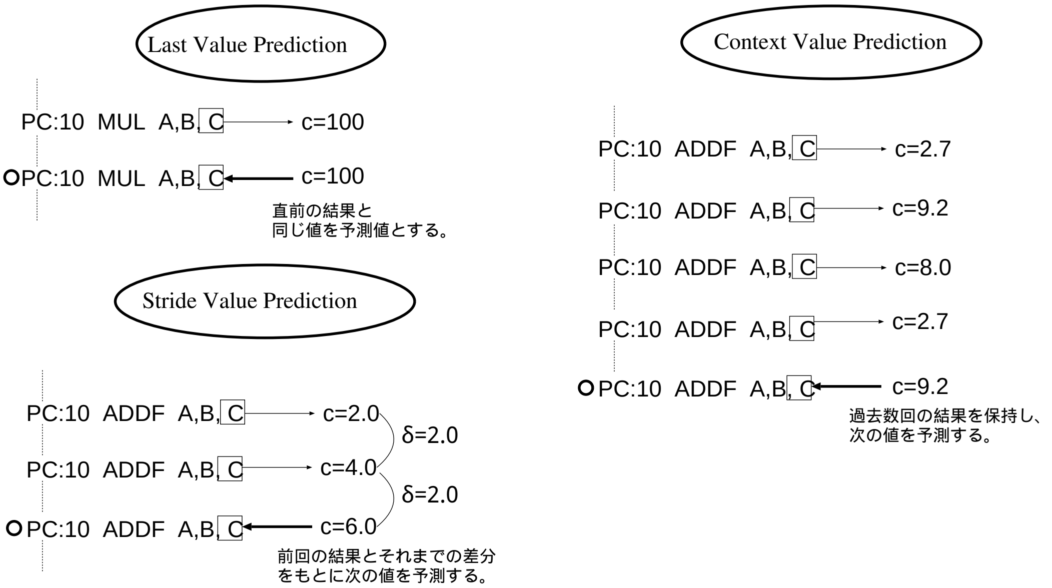
5.1 F0E*%9%F%C%W?t$K4p$E$/L?Na>v$_9~$_$NDjNIE*I>2A

L?Na>v$_9~$_$NC1FH$N8z2LrB,Dj9$k!#@h$K=RY?h&$K!"K\%W%m%;%C%5$K$ODj?t$*hS%m!<%+%kJQ?tNCMr3F!9J];}9k%1%8%9%?$,B8:_$9$k!#$=$N7k2L!"1i;;A08e$K9Tol$kDj?t!&%m!<%+%kJQ?t$N%9%?%C/>eXN%m!<%I(iload,bipush L?NaEy)!"5Z$S%9%?%C/$+iN%9%H%"(istore,pop L?NaEy) A`:n$r%9%?%C/$r2p$;$:1i;;L?Na$H>v$_9~sG%1%8%9%?Fb$G=hM}$9k3H,2DG=HJ$k!#SPEC-JVM98 $rMQ$$$FL?Na>v$_9~$_Kh$kL?Na:o8:?t$rB,Dj7?!#7k2L$rI=9$K<($9!#L?Na:o8:?t$O!"2 L?Na$r1 L?Na$K>v$_9~$s$@$H$-$K1!"3 L?Na$r1 L?Na$K>v$_9~$s$@$H$-$K2!"4 L?Na$r1 L?Na$K>v$_9~$s$@$H$-$K3 L?Na:o8:H7F=$N9g7W$r5aa?!#L?Na>v$_9~$_2DG=$JL?Na$NAH9g$;$O%1%8%9%?$,$=li$NL?Na$,;HMQ9kCM$rA4$FJ];}7F$$$kI,MW$,$"$j!"FC$K%m!<%+%kJQ?t$KCmL\$7$F!"%m!<%+%kJQ?t$rJ];}9k%1%8%9%??t$rJQ2=$5$;$J$,$iL?Na>v$_9~$_$N8z2L$rB,Dj7?!#%m!<%+%kJQ?t%1%8%9%??t$,4 NH$-$3li$N%1%8%9%?$O%m!<%+%kJQ?t0!A3 NCMrJ];}$7!"8 NH$-0!A7 NCMrJ];}$7!"16 NH$-0!A15 NCMrJ];}9k!#Java %3%s%Q%$%i$O%3%s%Q%$%k;~$KG-k@$1DcHVCO$N%m!<%+%kJQ?t$r;HMQ$9kh$&$K9kNGDL>o$ODcHVCO$N%m!<%+%kJQ?t$[$I;HMQIQEY$,9b$$!#$^$?Dj?t$rJ];}$9$k%3%s%9%?%s%H%1%8%9%?$K$D$$$F$O>o;~2 DH8GDj$7!">o$KL?Na>v$_9~$_$,2DG=G"$kH9$k!#6 DN%Y%s%A%^!<%/$r%F%9%H$7$?7k2L!"%m!<%+%kJQ?t%1%8%9%??t$,L58B$H2>Dj7?H-$NL?Na>v$_9~$_$KhkL?Na:o8:?t$O:GDc22%$+$i:G9b42%$^GNCM$r<($7!"J?6Q$O31%$G$"$C$?!#0lJ}%m!<%+%kJQ?t%1%8%9%??t$,4 NH$-$NJ?6QCM$O23.86%!"8 NH$-27.43%!"16 NH$-31.24%$r<(7?!#3N7k2L$+$iL?Na>v$_9~$_KI,MWJ%m!<%+%kJQ?t%1%8%9%??t$O8 $G==J,$G$"$k3H$,$o$+$k!#

5.2 %G!<%?Ej5!$NDjNIE*I>2A

<!$K%G!<%?Ej5!$NM-8z@-$r8!F$$9k?aK%Q%$%W%i%$%s$N%9%H!<%kMW0x$K4X9kI>2A$r9T$&!#%G!<%?Ej5!$,M-8z$HJkNOK\Mh$G$"lP%Q%$%W%i%$%s$,%9%H!<%k$7$F$$$?>lLL$G%G!<%?CMM=B,$KhkEj5!E*<B9TKh$j%9%H!<%k$r2sHr9k3HG"C?!#K\%W%m%;%C%5$O%G!<%?Ej5!$rMxMQ7J$$>u672<GO2<$N>l9g$K%G!<%?0MB8Kh$k%Q%$%W%i%$%s%9%H!<%k$,H/@8$9$k!#

1. 1i;;$K2 %5%$%/%kMW9k@h9TL?Na(Nc$($P>h;;L?Na) $N7k2L$rD>8e$N8eB3L?Na$,;HMQ9kH-(*2cycle*)
2. =|;;L?Na$r<B9TCf$K8eB3L?Na$,$=$N7k2L$r;HMQ9kH-(*div*)
3. %*%Z%i%s%I%9%?%C/$*$h$S%m!<%+%kJQ?t%-%c%C%7%e$+$i%m!<%I$7$F$$$kCM$r8eB3L?Na$,;HMQ9kH-(*Java_stack*)
4. %R!<%W%-%c%C%7%e$+$i%m!<%I7F$$$kCM$r8eB3L?Na$,;HMQ9kH-(*Heap cache*)
5. ;2>HJQ4%F!<%V%k$G%_%9%R%C%H$,H/@8$7$?H-



?^9: <o!%$N%G!<%?M=B,<jK!

I=9: A4<B9TL?Na?t$K@j$a$k:o8:$7$?L?Na?t$N3d9g

%m!<%+%kJQ?t	compress	jess	db	javac	mpegaudio	mtrt
4	30.69%	20.74%	20.23%	22.60%	24.26%	24.64%
8	37.77%	23.55%	21.26%	26.44%	29.70%	25.89%
16	42.02%	29.64%	22.27%	27.57%	40.05%	25.91%
!g	42.02%	29.64%	22.27%	27.57%	40.14%	25.91%

I=10: L?Na%0%k!<%WFbLu

2cycle	*imul,lmul,fadd,fsub,fmul,dadd,dsub,dmul*
div	*idiv,ldiv,fdiv,ddiv,irem,lrem,frem,drem*
Java_stack	*iload_n,lload_n,fload_n,dload_n,aload_n (n* $0%1%8%9%?30)
Heap cache	*iaload,laload,fload,daload,aaload,baload,caload* *saload,getfield,instanceof,arraylength*

>e5-$N%Q%$%W%i%$%s%9%H!<%k$NMW0x4HK^Ha$?L?Na$NFbLu$rI=10$K<($9!#

@h$ND4::$Khj!"%*%Z%i%s%I%9%?%C%/$*$h$S%m!<%+%kJQ?t%-%c%C%7%e$O$[$\100%$N%R%C%HN($rF@k3H,G-kHo+CF$$$kNG%*%Z%i%s%I%9%?%C%/$*$h$S%m!<%+%kJQ?t%-%c%C%7%e$+iO1%5%$%/%k$GCM$r<hF@$9k3H,G-!"%Q%$%W%i%$%s$,Dd;_$9kN$O%*%Z%i%s%I%9%?%C%/%-%c%C%7%e$*$h$S%m!<%+%kJQ?t%-%c%C%7%eFI$_=P$7L?Na$ND>8e$K$=$NCM$r;HMQ$9$kL?Na$,Mh$?$H$-$K8BkH2>Dj9k!#$^$?;2>HJQ49I=KD$$$F$b%U%#!<%k%I;2>HJQ49I=!"%a%=%C%I;2>HJQ49I=KD$$$FO[$\100%$N%R%C%HN($rF@$k3H$,$G$-$k3H$,$o$+$C$F$$$k$?$a3N2DNI=$K4X$9$kL?Na$K$D$$$F$O%l%$%F%s%7$,H/@8$7$J$$$H2>Dj9k!#%*%V%8%'%/%H;2>H$K8B$j!";2>HI=%_%9;~$N%Z%J%k%F%#$r9MN8$9$kI,MW$,$"$k!#$7$?$,CF%G!<%?Ej5!$N<jK!$rMQ$$$F0J2<NCMrM=B,$7Ej5!E*<B9T$r9T$&$3HKhj%Q%$%W%i%$%s%9%H!<%k$N2sHr$rA@$&!#

1. 2%5%$%/%k1i;;L?Na$N<B9T7k2L
2. =|;;L?Na<B9T7k2L
3. Java%9%?%C%/%-%c%C%7%e$NCM
4. %R!<%W%-%c%C%7%e$NCM

5.3 7k2LCM$N6I=j@-$K4X9kI>2A

%G!<%?M=B,$NJ}K!$H7FLast Value Prediction(LVP)$rMQ$$$?!#LVP$OA0=R$7$?$h$&$K2a5n$NMzNrJ];}1$D$GM=B,BP>]L?Na$N7k2L$rM=B,$9$kJ}<0$G$"$jLVP$,9b$$M=B,E*CfN(rbD?aK$OBP>]L?Na$N7k2L$,0"B3$7$FF1$8G"k3H,5aailk!#9JoA<B9T%W%m%0%i%`NCMN6I=j@-(Value Locality)$,$=N^^LVPNM=B,E*CfN($K7R$,k3HHJj!"JVM$,<B9T$9$kJava%P%$%H%3!<%I$N6I=j@-$,=EMWG"k3H,o+$k!#$=3GJava%W%m%;%C%5K*1kCM$N6I=j@-$K$D$$$FSPEC-JVM98$rMQ$$$FB,Dj$r9T$C$?!#I=11$OA0=R7?%Q%$%W%i%$%s%9%H!<%k$rH/@8$5$;$kL?Na%0%k!<%WKD$$$F!"L?Na$NM=B,CM$,A02s$=$NL?Na$r<B9T$7$?$H$-$N7k2L$H0lCW$7$?3d9g$r<(7F$$$k!#

3N7k2Lhj!"1i;;L?Na$N6I=j@-!"$9Jo$A1i;;L?Na$N<B9T7k2LKBP9$kLVP$N8z2L$O*2Cycle*$GJ?6Q33.56%!"*div*$GJ?6Q22.83%$HDc$$CM$KN1$^CF$$$k3H$,$o$+$k!#1i;;7k2LXNLVPO"$^$j8z2Lrb$?$J$$!#7+$7Java%9%?%C%/5Z$S%R!<%W$+$i$N%m!<%IL?Na$KBP7F$O*Java-stack*$GJ?6Q58%!"*Heap cache*$GJ?6Q52%$N%R%C%HH^$:$^$:$NCM$r;D$7$?!#A4<B9TL?Na$K@jak%a%b%j%m!<%IL?Na$NB?$5$+$i$b1i;;L?Na$NM=B,E*CfNhj$b%a%b%j$NCM$rM=B,$9k[$&$,=EMW@-$,9b$/!"LVPKh$k%G!<%?Ej5!$O=<J,$K8z2L$,$"$k$H8+9~$^lk3H$,$G$-$k!#

5.4 %5%$%/%k?tC10L$GB,Dj7?Java%W%m%;%C%5$NI>2A

%-%c%C%7%e$d%"%I%l%9JQ49I=$b9MN8$KF~$l$?L?Na>v$_9~$_5Z$S%G!<%?Ej5!$N8z2L$r%5%$%/%k?tC10L$GB,Dj9k!#

5.4.1 B,Dj>r7o

B,Dj$O%m!<%+%kJQ?t%l%8%9%??t$,0!"4!"8!"16$N4<oN`$NH-$KJ,$1$F9T$C$?!#L?Na>v$_9~$_!"%G!<%?Ej5!$r9ToJ$/$F$b%m!<%+%kJQ?t%l%8%9%?$,$"$k3HKh$jJava%9%?%C%/%-%c%C%7%e$X$N%"%/%;%9$,8:$j!"%Q%$%W%i%$%s%9%H!<%k$N2s?t$,8:>/$7$F%5%$%/%k?t$rC;=L$9k3H,G-$k!#=>$CF=l>lN%m!<%+%kJQ?t%l%8%9%??tK*1kL?Na>v$_9~$_8e$N%5%$%/%k?t!"%G!<%?Ej5!8e$N%5%$%/%k?t!"IAibE,MQ7J$+$C$?$H$-$N%5%$%/%k?t$N#3DrB,Dj7?!#3l$^$G$ND4::$r;29M$KJava%9%?%C%/%-%c%C%7%e$N%5%$%:$O16%-%m%P%$%H!"%R!<%W%-%c%C%7%e$N%5%$%:$O64%-%m%P%$%H$H7?!#$^$?9bB.%"%I%l%9JQ49I=KD$$$F$bF1MM$KD4::7k2L$r;29M$K%U%#!<%k%I;2>H!"%a%=%C%I;2>H!"%*%V%8%'%/%H;2>H$NJQ49I=$N%(%s%H%j?tr=l>$l256!"256!"1024$N4%&%'%$$H7?!#%m!<%+%kJQ?t%l%8%9%?$OCHV9f$K=>CF0HV$+$i%m!<%+%kJQ?tNCM,%l%8%9%?$K3JG<$5lF$*$j!"%l%8%9%?$K3JG<$5lF$$$k%m!<%+%kJQ?t$*$h$S%3%s%9%?%s%H$rA`:n9kL?Na$rBP>]$H7FL?Na>v$_9~$_$r9T$&!#%G!<%?Ej5!$N:]$O!"LVP$K4p$E$-A0=R$7$?1i;;L?Na

I=11: %Q%$%W%i%$%s%9%H!<%k;~$N6I=j@-!#s10 $GB,Dj!#

	compress	jess	db	javac	mpegaudio	mtrt	J?6Q
2cycle	45.83%	13.63%	50.00%	58.95%	3.90%	19.10%	33.56%
div	6.14%	57.71%	8.73%	16.75%	21.64%	26.02%	22.83%
Java_stack	73.71%	58.67%	54.36%	59.59%	58.86%	42.87%	58.01%
Heap cache	59.30%	66.51%	51.78%	54.68%	48.54%	33.39%	52.36%

I=12: 3F!9KMW9$k%5%$%/%k?t

2cycle	2
div	C1@:EY 16 G\@:EY 30
Java_stack cache	@h=R$ND4::$hj[$\100%%-%&%C%7%e%R%C%H$KD->o$K 1
Heap cache	%-%&%C%7%e%R%C%H;~1 %_%9;~20
%*%V%8%'%/%H;2>HJQ49I=	%_%9;~20

$N7k2L$*hS%a%b%j%"%/%;%9L?NaNCMrM=B,9k!#@hDx$ND4::7k2L$+$i%*%Z%i%s%I%9%?%C%/NN0h!"%m!<%+%kJQ?tNN0h$*$h$S%R!<%W$X$N%a%b%j%"%/%;%9L?Na$KBP7F LVP $O=<J,M-8z$G$"$k3H$,$o$+$C$F$$$k!#%G!<%?Ej5!<:GT;~$N%Z%J%k%F%#$OI=12$ND L$jH9$k!#8 6M}$N@bL@$N:]$K$b=R$Y$?$h$&$K!"%G!<%?Ej5!$,30$l$?$H$-$N%Q%$%W%i%$%s%9%H!<%k$O%G!<%?Ej5!$r7J$+$C$?$H$-$K@8$8$k%Q%$%W%i%$%s%9%H!<%kKEy7$$$H2>Dj9k!#

%*%Z%i%s%I%9%?%C%/5Z$S%m!<%+%kJQ?t$X$N%"%/%;%9$K$D$$$F$O0JA0$ND4::$GL@$i$+$KJC$?$h$&$K$[$\I,$:$H$$$CFh$$$[$I%-%&%C%7%e$K%R%C%H9k$?$a!"8eB3L?Na$,%G!<%?0MB8$Khj%9%H!<%k7Fb=$N%Z%J%k%F%#$O1 %5%$%/%k$N$_$G:Q$`!#%R!<%W$X$N%"%/%;%9$N:]$N8eB3L?Na$N%G!<%?0MB8Kh$k%Z%J%k%F%#$K$D$$$F$O%R!<%W%-%&%C%7%e%R%C%H;~$O1 %5%$%/%k!"%_%9;~$O20 %5%$%/%kH9$k!#3 DN%"%I%9JQ49%F!<%V%kXN%"%/%;%9KD$$$F$O!"%*%V%8%'%/%H;2>HJQ49%F!<%V%kGO%F!<%V%k>e$KJQ49$CM$,:\$C$F$$$J$+$C$?>l9g$O%Z%J%k%F%#$20 %5%$%/%k$G<g5-21>e$GJQ49CMr$?$IkH2>Dj9k!#7+$7%U%#!<%k%I;2>HJQ49%F!<%V%k!"%a%=%C%I;2>HJQ49%F!<%V%kKD$$$F$O@h$ND4::hj$[$\I,$:JQ49$CM$,%R%C%H$9k3H,o+CF$$$kNGI,$:1 %5%$%/%kN_$GJQ49$CM$rF@$kH9$k!#$7$?$,CF%*%V%8%'%/%H;2>HJQ49%F!<%V%k$K8BDj$7$F%Z%J%k%F%#$r%R%C%H;~1 %5%$%/%k!"%_%9;~20 %5%$%/%k$H2>Dj$9$k!#$^$?%a%=%C%I8F$S=P$7!"%a%=%C%I5"4TL?Na$K$D$$$F$OFbIt>uBV$NB`Hr!"I|85$K18 %5%$%/%krMW9kbNH2>Dj7?!#3l0J30$NL?Na$K$D$$$F$O%Q%$%W%i%$%s$,%9%H!<%k9kH-$r=|$$$F!"%Z%J%k%F%#$,$J$/L?Na$,4 0N;9kbNH9$k!#LVP N?aNL?Na<B9T7k2L$rJ];}9k%F!<%V%k$NMFNL$OL58BG"kH2>Dj$7!"%G!<%?Ej5!$,2DG=$J>u67GO9Y$F%G!<%?Ej5!$r<B9T9k3HH9$k!#B,DjKOSPEC-JVM98 $rKaffe >e$GF0:n5;!"%-%&%C%7%e$dJQ49I=$N8z2L$b9MN8$7J,$i%G!<%?Ej5!!"L?Na>v$_9~$_$Khk%5%$%/%k?t$NJQ2=rB,Dj7$?!#7k2L$rI=13!AI=18$K<($9!#7k2L$OA4$F s1 GB,Dj7$?$bNG$"$k!#>eCJ$O<B9T$KMW7?%5%$%/%k?t$r<($7!"2<CJ3g8IFb$O%m!<%+%kJQ?t%1%8%9%?0!"L?Na>v$_9~$_$*$h$S%G!<%?Ej5!$r9ToJ$$>l9gKMW9$k%5%$%/%k?t$r100%$H7?H-NHfr<($9!#

5.4.2 B,Dj7k2L

%1%8%9%?$rIU2C$7$?$3HKhk%5%$%/%k?t:o8:$N8z2L$O%m!<%+%kJQ?t%1%8%9%??t 4 NH$-$K:G9b10.4%!"J?6Q3.9%!"8 NH$-$K:G9b11.5%!"J?6Q4.4%!"16 NH$-$K:G9b12.0%!"J?6Q4.7%G"k3H,o+C?!#%1%8%9%?IU2C$K2C$($FL?Na>v$_9~$_$r9TC?H-$N%5%$%/%k?t:o8:$N8z2L$O%m!<%+%kJQ?t%1%8%9%?$,4 NH

I=13: compress -s1

%m!<%+%k JQ?t	nothing	L?Na >v$_9~$_	%G!<%? Ej5!
0	3621970700 (100.00%)	—– (—)	2651281700 (73.20%)
4	3245169700 (89.60%)	2952053700 (81.50%)	2572722700 (71.03%)
8	3205611700 (88.50%)	2844873700 (78.54%)	2563204700 (70.77%)
16	3188766700 (88.04%)	2787343700 (76.96%)	2556705700 (70.59%)

I=14: jess -s1

%m!<%+%k JQ?t	nothing	L?Na >v$_9~$_	%G!<%? Ej5!
0	43545525 (100.00%)	—– (—)	36924601 (84.80%)
4	42651796 (97.95%)	40732487 (93.54%)	36324951 (83.42%)
8	42463166 (97.51%)	40283953 (92.51%)	36228016 (83.20%)
16	42443079 (97.47%)	39700139 (91.17%)	36216051 (83.17%)

I=15: db -s1

%m!<%+%k JQ?t	nothing	L?Na >v$_9~$_	%G!<%? Ej5!
0	7747483 (100.00%)	—– (—)	6989410 (90.22%)
4	7525327 (97.13%)	7122302 (91.93%)	6762827 (87.29%)
8	7481315 (96.56%)	7057753 (91.10%)	6736964 (86.96%)
16	7481291 (96.56%)	7037598 (90.84%)	6736095 (86.95%)

I=16: javac -s1

%m!<%+%k JQ?t	nothing	L?Na >v$_9~$_	%G!<%? Ej5!
0	44484493 (100.00%)	—– (—)	40996537 (92.16%)
4	42828771 (96.28%)	40556317 (91.17%)	40000626 (89.92%)
8	42581937 (95.72%)	39923511 (89.75%)	39865162 (89.62%)
16	42580565 (95.72%)	39808361 (89.49%)	39864927 (89.62%)

I=17: mpegaudio -s1

%m!<%+%k JQ?t	nothing	L?Na >v$_9~$_	%G!<%? Ej5!
0	381519824 (100.00%)	—– (—)	284331624 (74.53%)
4	375840024 (98.51%)	340270824 (89.19%)	284038024 (74.45%)
8	373955824 (98.02%)	333939824 (87.53%)	283063124 (74.19%)
16	369022624 (96.72%)	321889824 (84.37%)	279467424 (73.25%)

I=18: mtrt -s1

%m!<%+%k JQ?t	nothing	L?Na >v$_9~$_	%G!<%? Ej5!
0	367881600 (100.00%)	—– (—)	339110600 (92.18%)
4	358350000 (97.41%)	341387600 (92.80%)	334664200 (90.97%)
8	357749600 (97.25%)	339926600 (92.40%)	334156900 (90.83%)
16	356933700 (97.02%)	339096600 (92.18%)	333515300 (90.66%)

$-$K:G9b18.5%!"J?6Q10.0%!"8 NH$-$K:G9b22.5%!"J?6Q11.4%!"16 NH$-$K:G9b24.0%!"J?6Q12.5%G"$j!"%1%8%9%?IU2C$K2C$($F%G!<%?Ej5!$r9T$C$?$H$-$N%5%$%/%k?t:o8:8z2L$O%m!<%+%kJQ?t%1%8%9%?0 NH$-:G9b26.8%!"J?6Q15.5%!"4 NH$-:G9b29.0%!"J?6Q17.5%!"8 NH$-:G9b29.2%!"J?6Q17.4%!"16 NH$-:G9b29.4%!"J?6Q17.6%$G$"$C$?!#L?NaIQEY$K4X9kD4::hjo+kh$&$Kjess!"javac!"mtrt $H$$$C$?%a%=%C%I8F$S=P$7!"%a%=%C%I5"4TL?Na$,B?$$%Y%s%A%^!<%/$OA4%5%$%/%k?tK*1k%U%1!<%`$N:n@.!"I|85=hM}$,@jak3d9g$,Bg$-$/!"%G!<%?Ej5!$dL?Na>v$_9~$_$N8z2L$,$"$^$jI=$1$F$$$J$$$3H,o+$k!#0lJ}$=1i$NL?Na$N>/$J$$compress $dmpegaudio $H$$$C$?%Y%s%A%^!<%/$K$D$$$F$O%G!<%?Ej5!$Khj30%6a$/%5%$%/%k?t$r:o8:$9kH$N7k2L$rF@$?!#

6 $*$ojK

K\8&5fK*$$$F$OL?Na>v$_9~$_$H%G!<%?Ej5!$H$$$&2 DN<jK!$KCmL\$7$FFH<+$K2>Dj7?Java %W%m%;%C%5>e$G8DJL$K$=$N8z2LrB,Dj7$?!#

L?Na>v$_9~$_$O%9%?%C%/%H%C%W$X$NDj7?E*$JA`:n$r:o8:$9k3HKhj%W%m%;%C%5FbItK*1kL?Na?t$r:o8:$9kbNG$"$jK\%W%m%;%C%5K*$$$F$O9bB.$JCMNdjHjr2DG=H9$k%1%8%9%?$r@_1F3N<jK!$r<B8=$7$?!#B>J}%=%U%H%&%'%"$K<BAu9k3H$b2DG=$GL?Na>v$_9~$_$r9T$&JIT %3%s%Q%$%i$b3+H/$5$1$F$$$k!#3Nh&$KL?Na>v$_9~$_$O%9%?%C%/%^%7%s$NIT<+M3$5r4$/<+A3$K2r>C9k<jK!$GJ#;($J9=@.rI,MWH7J$$$3H,FCD9G"$k!#L?Na>v$_9~$_$GJ?6Q30%L?Na?t$r:o8:$G$-$k0U5AOBg-$$!#

0lJ}%G!<%?Ej5!$O%Q%$%W%i%$%s%9%H!<%k$r2r>C9k<jK!H7$F!"FC$K%*%Z%i%s%I%9%?%C%/!"%m!<%+%kJQ?t$*$h$S%R!<%W$X$N%"%/%;%9$N:]$K@8$8$k%Z%J%k%F%#$N2sHr$rL\E*$H7F$=$N8z2LrB,Dj7$?!#%G!<%?$NM=B,J}K!H7FOLVP $H$$$&bCHb4JC1$J<jCJ$rMxMQ7?7k2L!"1i;;L?Na$N7k2L$KBP9kM=B,E*CfN($O30% DxEY$HDc$/!"Java %9%?%C%/$d%R!<%WJI%a%b%jNCMNM=B,KD$$$F$bE*CfN($O50%DxEY$KN1$^C?!#%Q%$%W%i%$%s%9%H!<%kN[HsINMW0x$,Java %9%?%C%/$d%R!<%WXN%"%/%;%9K"k3H,o+CF$$$kNGM=B,<jK!rh$j9bEY$JbNH7!"E*CfN($N8~>e$r?^kI,MW,$"$k!#

L?Na>v$_9~$_$H%G!<%?Ej5!$OMF0W$KAH9g$;k3H,G-$k!#L?Na>v$_9~$_$KhC$F?7$?$K2DG=$HJk%G!<%?Ej5!BP>]$NL?Na$,8=lk3H$+$i2 DrAH9g$;$?H-$N8z2L$O:#2s8DJLKB,Dj7$?8z2L$NOBhjbBg-$$$H9M$($ilk!#7?$,$C$F%m!<%+%kJQ?t%1%8%9%?16 $N>l9g$K:G9b53%0J>e(compress)!"J?6Q30%$N%5%$%/%k?t$r:o8:$9k3H,G-$k!#L?Na>v$_9~$_$HB>$N9bB.2=<jK!$H$NAH9g$;$r8!F$$7$F$$$/3H$b=EMW$G$"$k!#

:#8e$N8!F$2]BjH7FO!"%R!<%W%-%c%C%7%e5Z$S%*%V%8%'%/%H;2>HJQ49I=$N2~NIKh$k%R%C%HN($N8~>e!"$=$7$FL?Na>v$_9~$_$HAH9g$;$F;HMQ9kJVM 9bB.2=$N<jK!$N:F8!F$$H$$$C$?E@$,5s2ilk!#

<UK-

K\8&5f$N5!2q$rM?$($F$/$@5C$?IYEDbC<#65<x$K?<?SJk<U0U$rI=$7$^$9!#$^$?!"K\8&5f$K

4X7FE,@Z$J8f;XF3$r;rC?CfEg9/I'=u65<x!"?9bC0lO:=u65<x!"8^Eg@5M5=u<j$K?4$+$i46<UCW$7$^$9!#:G8e$K!"K\8&5f$N6&F18&5f<TG"$k=EEDBg=u;a!";3ED9n<y;a$rO8$aF|:"$+$i8f=uNOD:$$$?5~ETBg3XBg3X1!>pJs3X8&5f2JDL?.>pJs%7%9%F%`@196IYED8&5f<<$N=t7;$K?4hj46<UCW7^$9!#

;29MJ88%

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7 O"B32 L?Na=P8=IQEY0lMw

I=19!A24$KO"B32 L?Na$K$D$$$F!"=P8=IQEY$N9b$$$bNr3F%Y%s%A%^!<%/4H$K<($9!#O"B32 L?NaN&$AL?Na>v$_9~$_$N2DG=JbNK$D$$$F$O1&Ms$K!}$r5-$9!#2 L?Na=P8=IQEY>e0LN&AGH>J,6a$/$NAH9g$;$,>v$_9~$_$NBP>]$G$"$k3H$,$o$+$k!#

I=19: compress

	IQEY	L?Na>v$_9~$_BP>]
%m!<%+%kJQ?t%m!<%I⇒ %R!<%Whj%m!<%I	14.9%	!}
%m!<%+%kJQ?t%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	7.3%	
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	6.9%	
Dj?t$N%W%C%7%e⇒ Hf3S	5.1%	!}
%m!<%+%kJQ?t%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	4.8%	
%m!<%+%kJQ?t%m!<%I⇒ $=$NB>$N%9%?%C%/A`:n	3.7%	!}
$=$NB>$N%9%?%C%/A`:n⇒ %R!<%W$h$j%m!<%I	3.3%	
Hf3S⇒ %R!<%WXN%9%H%"	3.1%	
%R!<%WXN%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	3.1%	
%m!<%+%kJQ?t%m!<%I⇒ Hf3S	3.1%	!}

I=20: jess

	IQEY	L?Na>v$_9~$_BP>]
%m!<%+%kJQ?t%m!<%I⇒ %R!<%Whj%m!<%I	17.6%	!}
%m!<%+%kJQ?t%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	8.2%	
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	7.1%	
%m!<%+%kJQ?t%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	4.2%	
%m!<%+%kJQ?t%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	4.8%	
%R!<%Whj%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	3.8%	
%m!<%+%kJQ?t%m!<%I⇒ J,4t	3.2%	!}
%R!<%Whj%m!<%I⇒ J,4t	2.3%	!}
Dj?t$N%W%C%7%e⇒ %a%=%C%I8F$S=P$7/5"4T	2.3%	
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%9%H%"	1.9%	!}

I=21: db

	IQEY	L?Na>v$_9~$_BP>]
%m!<%+%kJQ?t%m!<%I⇒ %R!<%Whj%m!<%I	16.7%	!}
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	12.8%	
%m!<%+%kJQ?t%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	9.0%	
%m!<%+%kJQ?t%m!<%I⇒ Hf3S	5.4%	!}
%m!<%+%kJQ?t%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	5.4%	
%m!<%+%kJQ?t%m!<%I⇒ J,4t	5.0%	!}
Hf3S⇒ %R!<%Whj%m!<%I	4.1%	
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%9%H%"	3.6%	!}
%m!<%+%kJQ?t%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	2.8%	
%R!<%Whj%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	2.4%	

I=22: javac

javac	IQEY	L?Na>v$_9~$_BP>]
%m!<%+%kJQ?t%m!<%I⇒ %R!<%Whj%m!<%I	13.8%	!}
%m!<%+%kJQ?t%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	7.5%	
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	5.3%	
%m!<%+%kJQ?t%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	4.3%	
%m!<%+%kJQ?t%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	3.6%	
%m!<%+%kJQ?t%m!<%I⇒ J,4t	2.9%	!}
%R!<%Whj%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	2.8%	!}
%m!<%+%kJQ?t%m!<%I⇒ J,4t	2.3%	!}
%R!<%WXN%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	2.2%	
Hf3S⇒ %R!<%WXN%9%H%"	2.1%	

I=23: mepgaudio

	IQEY	L?Na>v$_9~$_BP>]
%m!<%+%kJQ?t%m!<%I⇒ %R!<%Whj%m!<%I	10.9%	!}
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	10.6%	
%m!<%+%kJQ?t%m!<%I⇒ Dj?t$N%W%C%7%e	9.0%	
%m!<%+%kJQ?t%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	7.5%	
Dj?t$N%W%C%7%e⇒ %R!<%W$h$j%m!<%I	5.5%	!}
%m!<%+%kJQ?t%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	5.5%	
%R!<%Whj%m!<%I⇒ Hf3S	5.0%	
Hf3S⇒ %m!<%+%kJQ?t%9%H%"	4.6%	!}
Dj?t$N%W%C%7%e⇒ Hf3S	4.3%	!}
Hf3S⇒ Hf3S	3.1%	

I=24: mtrt

	IQEY	L?Na>v$_9~$_BP>]
%m!<%+%kJQ?t%m!<%I⇒ %R!<%Whj%m!<%I	15.2%	!}
%R!<%Whj%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	11.0%	
%m!<%+%kJQ?t%m!<%I⇒ %a%=%C%I8F$S=P$7/5"4T	8.8%	!}
%m!<%+%kJQ?t%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	5.7%	
%m!<%+%kJQ?t%m!<%I⇒ Dj?t$N%W%C%7%e	3.1%	
%R!<%Whj%m!<%I⇒ %m!<%+%kJQ?t%m!<%I	5.0%	
Hf3S⇒ J,4t	2.2%	
Dj?t$N%W%C%7%e⇒ %a%=%C%I8F$S=P$7/5"4T	1.9%	
%R!<%WXN%9%H%"⇒ %m!<%+%kJQ?t%m!<%I	1.7%	
Dj?t$N%W%C%7%e⇒ %m!<%+%kJQ?t%m!<%I	1.7%	