6u4VE*@)Ls$NEAGE$K4pE/Dj@-E*6u4V9=B$$NF1Dj

==2O Bn;J* @P9u 9@* @PED 5|*

Spatial Constraint Propagation for Identifying Qualitative Spatial Structure

Takushi SOGO, Hiroshi ISHIGURO and Toru ISHIDA

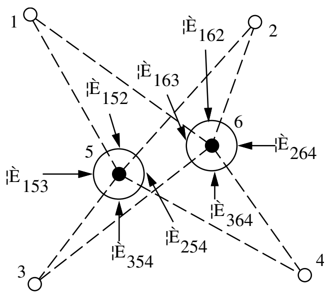
We propose a method for building a qualitative spatial model of landmarks based on geometrical constraints. The model is built by iterating the following steps: (1) observing qualitative motions of moving objects from the landmarks, (2) partitioning the landmarks into two groups, (3) acquiring *three point constraints*, and (4) propagating the constraints.

We have applied this method to qualitative localization of vision sensors of a *distributed vision system* which consists of several vision sensors and evaluated it with simulations.

1 O8aK

<+N'0\F0%m%\%C%HJI$N8&5fJ,Ln$G$O, J#?t$N%i%s%I%^!<%/$N0LCV$r4QB,KhCF3MF@9k=hM}$OIQHK$K9Tol$k. Nc$($P?^ 1 Nh$&$KJ#?t$NCOE@$+$i%i%s%I%^!<%/$N4V$N3QEY$r4QB,7F%i%s%I%^!<%/$*hS4QB,COE@$NJ?LL>e$N0LCV $\boldsymbol{p}_i = (x_i, y_i) (1 \le i \le n)$ $r5a$akK$O, 0lHL7A$,<!Nh$&$KI=5l$kHs@~7AO"N)J}Dx<0$r2r$/.

$$\cos\theta_{ijk} = \frac{(\boldsymbol{p}_i - \boldsymbol{p}_j)\cdot(\boldsymbol{p}_k - \boldsymbol{p}_j)}{|\boldsymbol{p}_i - \boldsymbol{p}_j||\boldsymbol{p}_k - \boldsymbol{p}_j|} \quad (1 \le i, j, k \le n)$$



?^ 1: 4QB,$NNc

7+$7, 9-$$6u4VKo$?$kB??t$N%i%s%I%^!<%/$N0LCV$r3MF@$9$k>l9g$O4QB,8m:9$N1F6A$,Bg$-$/Jk$?$a, 3NO"N)J}Dx<0KBP7$FJQ?t$N>C5n$d?tCM$NBeF~$r7+$jJV9H$$$&C1=c$J<jK!$G$O,

- $=$N2aDx$GJ}Dx<0$,L7=b9k$?$a$K2r$r5aak3H$,$G$-$J$$
- 8m:9$NC_@Q$KhC$F, 5a$a$?2r$,<B:]$N0LCV$H$OA4$/0[Jk

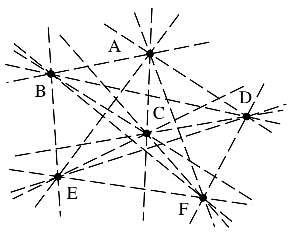
JI$H$$$C$?$3H,5/$-$k. 3Nh&$J>l9g$K$O6u4V$rJ#?t$NItJ,6u4V$KJ,$1, $=$l$>$l$N6u4V$K$*$$$F%i%s%I%^!<%/$N0LCV$r5a$a, $=$lirE}9g7FA4BN$N%i%s%I%^!<%/$N0LCV$r5a$akJ$I, 8m:9$N1F6A$r>/$J$/$9k?aN9)IW$,I,MW$HJk.

%i%s%I%^!<%/$N0LCV$r?tCM$GI=8=$9$kDjNLE*$J%b%G%k$N3MF@$,L\E*G"$k8B$jO3Nh$&$J8m:9$NLdBj$OHr1ilJ$$. 7+$7, <+N'0\F0%m%\%C%H$N%J%S%2!<%7%g%sJIGODj@-E*$JI=8=$Khk%b%G%k$,F@$ill$P==J,$J>l9g$bB?$$ [1][2]. Dj@-E*$JI=8=$Khk%b%G%kHO, Nc$($PG$0U$N 3 E@NJBV=g=x (1&2sj^$?$O:82s$j) KhCF0LCV4X78$rI=8=$9kbNG$"$k [3].

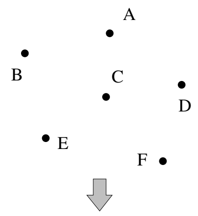
3Nh&$JDj@-E*$J%b%G%k$r8zN($h$/3MF@$G$-$l$P, $=$NE,MQNN0h$O9-$$. 7+$7, =>Mh$NDj@-E*$JI=8=$K4X9k8&5fO"i+8a%b%G%k$,M?$(il$F$$$k3H$rA0Ds$H7F$*$j [1][4], 3MF@$K4X$9$k8&5f$O$J$$.

K\O@J8GO, J#?t$N%i%s%I%^!<%/$NDj@-E*$J0LCV4X78$NI=8=9k6u4V%b%G%k$r, 4v2?E*$J@)Ls$rMQ$$$F3MF@9k<jK!$rDs0F$9$k. 3N<jK!$O, %i%s%I%^!<%/H=$N4V$r0\F0$9$kJ*BN$N1?F0$N4X78$r4QB,$7, $=$lKhCFF@il$k4v2?E*$J@)Ls$r6u4V%b%G%k$KE,MQ9k3H$G%i%s%I%^!<%/$NDj@-E*$J0LCV4X78$r3MF@9kbNG"$k. 6u4V%b%G%k$N3MF@KO4v2?E*$J@)Ls$N$_$rMQ$$, ?tCME*$J@)Ls$OA4$/MQ$$$J$$. K\<jK!Khj, Nc($P0LCV4X78$NITL@$JB??t$N;k3P%;%s%5$+$i0\F0J*BN$N1?F0$r4QB,9k3H$G, $=$liNDj@-E*$J0LCV4X78$r3MF@9k3H

*5~ETBg3XBg3X1!9)3X8&5f2J>pJs9)3X@l96



?^ 2: Dj@-E*$J0LCV4X78$NI=8=



ABC: +	ACE: −	BCD: +	BEF: +
ABD: +	ACF: +	BCE: −	CDE: −
ABE: +	ADE: −	BCF: −	CDF: −
ABF: +	ADF: −	BDE: −	CEF: +
ACD: +	AEF: +	BDF: −	DEF: +

?^ 3: Dj@-E*6u4V%b%G%k

$,$G$-$k.

0J2<GO, $^$:K\8&5f$G07$&Dj@-E*$J6u4V%b%G%k$K$D$$$F=RYk. <!K=$N3MF@$N$?$a$N<o!9$N4QB,$N7ABV, 3 E@@)Ls$K$D$$$F=R$Y, :G8e$KK\<jK!$rMQ$$$F;k3P%;%s%572$NDj@-E*$J0LCV4X78$r3MF@$9$k%7%_%e%l!<%7%g%s$r9T$$, $=$NM-8z@-KD$$$F8!>Z9k.

2 Dj@-E*6u4V%b%G%k$H4QB,7ABV

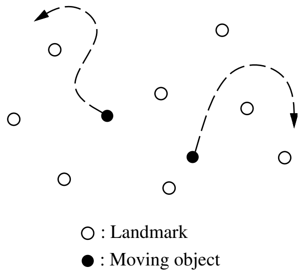
2.1 Dj@-E*6u4V%b%G%k

K\8&5fGO, ?^ 2 Nh$&$KJ#?t$NE@$NDj@-E*$J0LCV4X78$rG$0U$N 2 E@rDLkD>@~KBP7$FB>$NE@$NB8:_$9$kJ}8~$KhC$FI=8=$9$k.

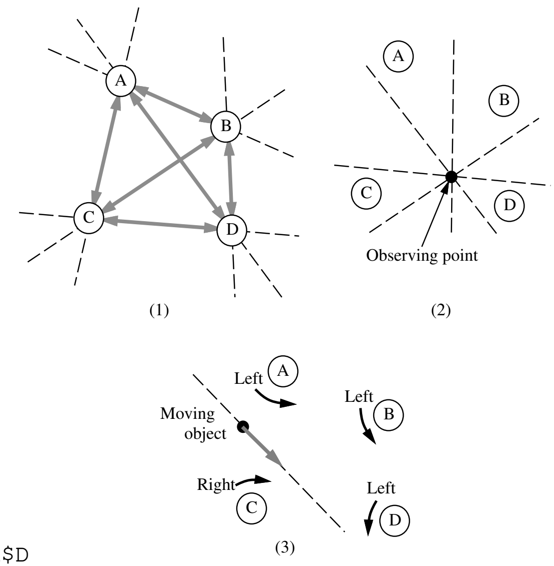
D>@~$,DL$kE@$r, l_j H9kH, 3ND>@~KBP9$kE@ l_k $N0LCV$O3liNE@NJBV=g=xKhCF<!Nh$&$KI=8=9k3H$,$G$-$k.

- $l_i \to l_j \to l_k$ $,:8$^oj!$l_i l_j l_k = +$
- $l_i \to l_j \to l_k$ $,1&$^oj!$l_i l_j l_k = -$

hj0lHLKO, 2 E@rDLkD>@~$HB>$NE@$N0LCV4X78$O$=$l$i 3 E@$l_i$, l_j, $l_k(l_i < l_j < l_k)$ NJBV=g=xH7$FI=8=$G$-$k [3]. ?^ 3 O3$NI=8=$K4p$E$$$FE@$N0LCV4X78$rI=7?Dj@-E*6u4V%b%G%kG"$k.



?^ 4: 4D6-$N0lNc



?^ 5: 3 DN4QB,7ABV

2.2 4QB,7ABV

K\<jK!GO, ?^ 4 Nh$&$JJ#?t$N%i%s%I%^!<%/$N4V$r 1 D^$?$OJ#?t$NJ*BN$,0\F0$7$F$$$k4D6-K*$$$F, J*BN$N1?F0$H%i%s%I%^!<%/HN4X78$r4QB,$9k3HKhC$F, Dj@-E*6u4V%b%G%k$r3MF@9k$?$aKI,MWJ%i%s%I%^!<%/4V$N4v2?E*$J@)Ls$rF@$k.

J*, 0lHL$K%i%s%I%^!<%/$H$O%;%s%5$KhC$FMF0W$K8!=P9k3HNG$-$kFCD'E@G"k,, %;%s%5<+?H$N0LCV$r3MF@9k>l9gKO%;%s%5$r%i%s%I%^!<%/$H8FV3HK9k.

4QB,KO<!$N 3 DN7ABV$,9M$(il$k.

1. 3F%i%s%I%^!<%/$+$iB>$N%i%s%I%^!<%/$N0LCV$r4QB,$9$k (?^ 5(1)). 3l$O6u4V$KB??tG[CV5l$?%;%s%5$,8_$$$N0LCV$r4QB,$9k3HKhC$F%;%s%5$N0LCV4X78$r3MF@$9$k>l9g$JIKAjEv9k. 3N4QB,KhCF, 4QB,COE@$N%i%s%I%^!<%/$HB>$N 1 DN%i%s%I%^!<%/rDLkD>@~KBP7F=$NB>$N%i%s%I%^!<%/$,B8:_$9$kJ}8~$rCNk3H,G-$k.

2. G$0U$NCOE@$+$i%i%s%I%^!<%/$N0LCV$r4QB,9k (?^

$5(2)$). \$3\$1\$OG\$0U\$NCOE@\$+\$i0\F0%m%\%C%H\$N;}\$D %;%s%5\$K\$h\$C\$F%i%s%I%^!<%/\$N0LCV\$r4QB,\$9\$k\$3 \$H\$G, %i%s%I%^!<%/\$N0LCV4X78\$r3MF@\$9\$k>l9g\$KAj Ev\$9\$k. \$3\$N4QB,\$K\$h\$C\$F, 4QB,COE@\$rDL\$kG\$0U\$N D>@~\$KBP\$7\$F3F%i%s%I%^!<%/\$NB8:_\$9\$kJ}8~\$rCN \$k\$3\$H\$,\$G\$-\$k.

3. 3F%i%s%I%^!<%/\$+\$iJ*BN\$N0\F0J}8~\$rF1;~\$K4QB, \$9\$k (?^ $5(3)$). \$3\$1\$O 1. \$HF1MM\$K6u4V\$KB??tG[CV\$5\$1\$?%;%s%5\$+\$i, %;%s%50J30\$N8!=P\$7\$d\$9\$\$J* BN\$r4QB,\$7\$F%;%s%5\$N0LCV4X78\$r3MF@\$9\$k>l9g\$K AjEv\$9\$k. \$3\$N4QB,\$K\$h\$C\$F, J*BN\$N0\F050@W\$K BP\$7\$F%i%s%I%^!<%/\$,B8:_\$9\$kJ}8~\$rCN\$k\$3\$H\$, \$G\$-\$k\$,, \$3\$1\$OK\<AE*\$K\$O 2. \$N4QB,\$K\$h\$C\$F\$@ \$i\$1\$k>pJs\$HF1\$8\$b\$N\$G\$"\$k.

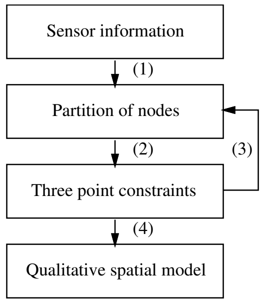
1. \$N4QB,\$K\$h\$C\$FF@\$i\$1\$k>pJs\$ODj@-E*6u4V%b%G%k \$K\$*\$1\$k@)Ls\$KD>@\BP1~\$9\$k\$?\$a, G\$0U\$N%i%s%I%^!<%/ \$+\$i4QB,\$r9T\$&\$3\$H\$K\$h\$C\$F6u4V%b%G%k\$r3MF@\$9\$k\$3 \$H\$,\$G\$-\$k. =>\$C\$F\$3\$N4QB,\$N>l9g\$O6u4V%b%G%k\$N3MF@ <jK!\$K\$D\$\$\$F5DO@\$9\$Y\$-\$3\$H\$O\$J\$\$. \$7\$+\$7, <B4D6-\$K \$*\$\$\$F%;%s%5\$H\$7\$F;k3P%;%s%5\$rMQ\$\$\$?>l9g\$J\$I, <B:] \$K\$O8_\$\$\$N%;%s%5\$r8!=P\$9\$k\$3\$H\$O:\$Fq\$G\$"\$k\$3\$H\$b B?\$/, \$3\$N\$h\$&\$J4QB,\$r9T\$&\$3\$H\$N\$G\$-\$k>l9g\$O8B\$i\$l \$F\$\$\$k.

2. \$O0lHLE*\$J4QB,7ABV\$G\$"\$j, \$3\$N\$h\$&\$J4QB,\$K\$h\$C \$FDj@-E*6u4V%b%G%k\$K\$*\$1\$k%m%\%C%H\$N0LCV7h\$a\$r9T \$\$, M6F3\$r9T\$C\$?8&5f\$,\$"\$k [1]. C"\$7, \$3\$3\$GMQ\$\$\$i\$l \$?6u4V%b%G%k\$O, %m%\%C%H\$,;k3PE*\$KH/8+\$7\$d\$9\$\$2hA| FCD'\$r%i%s%I%^!<%/\$H\$7\$F\$"\$i\$+\$8\$aM?\$(\$i\$1\$?\$b\$N \$G\$"\$j, \$3\$N8&5f\$G\$ODj@-E*6u4V%b%G%k\$N3MF@\$O9T\$o\$l \$F\$\$\$J\$\$.

2. \$N>l9g\$O3FCOE@\$G4QB,\$7\$?%i%s%I%^!<%/\$rF1Dj\$9 \$kI,MW\$,\$"\$j, %;%s%5\$H\$7\$F;k3P%;%s%5\$J\$I\$rMQ\$\$\$?>l 9g\$K\$OF1Dj\$O:\$Fq\$G\$"\$k\$N\$KBP\$7\$F, 3. \$N>l9g\$O5U\$K3F %i%s%I%^!<%/\$+\$i4QB,\$7\$?J*BN\$rF1Dj\$9\$kI,MW\$,\$J\$\$ \$b\$N\$N, DL>oJ*BN\$O>/?t\$G\$"\$jF1Dj\$OHf3SE*MF0W\$G\$"\$k \$H\$\$\$&FCD'\$,\$"\$k.

K\<jK!\$O, 2., 3. \$N4QB,\$K\$h\$C\$FF@\$i\$1\$k, \$"\$kD>@~ \$K\$h\$k4v2?E*\$KL7=b\$N\$J\$\$%i%s%I%^!<%/\$NJ,3d (Nc\$(\$P ?^ 5 \$N>l9g\$G\$O $\{ABD\}$ \$H $\{C\}$ \$"\$k\$\$\$O $\{AB\}$ \$H $\{CD\}$ \$J\$I\$NJ,3d) \$K4p\$E\$\$\$FDj@-E*6u4V%b%G%k\$r3MF@ \$9\$k. \$J\$*, \$3\$N?^\$N>l9g\$O $\{AD\}$ \$H $\{BC\}$ \$H\$\$\$&J, 3d\$O\$"\$jF@\$:, 4QB,\$5\$1\$J\$\$.

Cm0U\$9\$Y\$-\$3\$H\$O, 6u4V%b%G%k\$N3MF@\$KI,MW\$J\$N\$O\$3 \$N\$h\$&\$J%i%s%I%^!<%/\$NJ,3d\$N\$_\$G\$"\$j, D>@~\$N0LCV\$d J}8~, \$9\$J\$o\$A 2. \$N>l9g\$G\$O4QB,COE@\$dD>@~\$NJ}8~, 3. \$N>l9g\$G\$OJ*BN\$N0LCV\$d1?F0J}8~\$OI,MW\$J\$\$\$H\$\$\$&\$3 \$H\$G\$"\$k.



?^ 6: Dj@-E*6u4V%b%G%k\$N3MF@<j=g

3 Dj@-E*6u4V%b%G%k\$N3MF@

3.1 35MW

Dj@-E*6u4V%b%G%k\$O<!\$N<j=g\$r7+\$jJV\$9\$3\$H\$K\$h\$C \$F3MF@\$9\$k\$3\$H\$,\$G\$-\$k (?^ 6). 0J2<, %i%s%I%^!<%/\$r %N!<%I\$H8F\$V.

1. 4QB,>pJs\$+\$i%N!<%I\$NJ,3d\$rF@\$k.

2. %N!<%I\$NJ,3d\$+\$i 3 E@@)Ls\$rF@\$k.

3. F@\$i\$1\$? 3 E@@)Ls\$+\$i?7\$?\$J%N!<%I\$NJ,3d\$rF@\$F, :F\$S 3 E@@)Ls\$rF@\$k.

4. 3 E@@)Ls\$+\$iDj@-E*6u4V%b%G%k\$rF@\$k.

1. \$N4QB,>pJs\$+\$i\$N%N!<%I\$NJ,3d\$N3MF@\$O, ?^ 5 \$K<(\$7\$?\$h\$&\$K, G\$0U\$NCOE@\$+\$i\$N%N!<%I\$N0LCV\$N4QB,, \$^ \$?\$O3F%N!<%I\$+\$i\$NJ*BN\$N0\F0J}8~\$N4QB,\$K\$h\$C\$F\$J \$5\$1\$k.

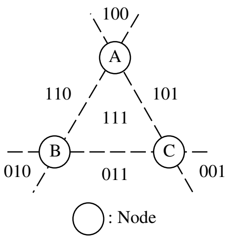
3.2 3 E@@)Ls\$N3MF@

\$"\$k%N!<%I X \$HB>\$N%N!<%I\$N0LCV4X78\$O, X \$H\$O0[\$J\$kG\$0U\$N 3 \$D\$N%N!<%I A, B, C \$KBP\$9\$k0LCV, \$9\$J \$o\$A, A, B, C \$rDL\$k 3 K\$ND>@~ AB, AC, BC \$K\$h\$C \$F:n\$i\$1\$k?^ 7 \$N 7 \$D\$NNN0h

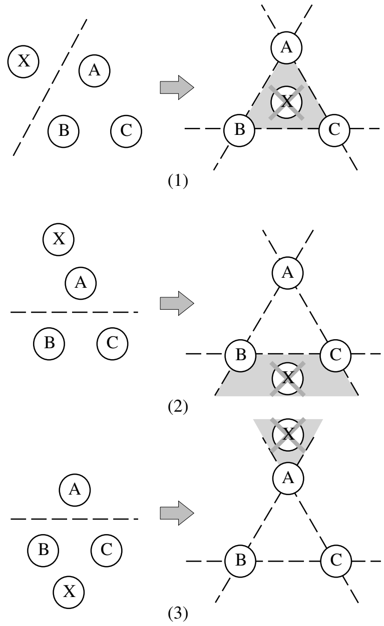
$$001,\ 010,\ 011,\ 100,\ 101,\ 110,\ 111$$

\$N\$&\$A, X \$,B8:_\$9\$kNN0h\$K\$h\$C\$FI=8=\$9\$k\$3\$H\$,\$G\$- \$k. X \$H A, B, C \$N0LCV4X78\$r\$3\$N\$h\$&\$KI=8=\$9\$k\$3 \$H\$G, 4QB,\$K\$h\$C\$FF@\$i\$1\$?%N!<%I\$NJ,3d\$+\$i X \$NB8 :_\$7\$&\$kNN0h\$N@)Ls\$rI=\$9 3 E@@)Ls\$rF@\$k\$3\$H\$,\$G\$- \$k.

A, B, C \$H X \$K4X\$9\$kJ,3d\$,F@\$i\$1\$?\$H\$-, 4v2?E* \$J@)Ls\$r9MN8\$9\$k\$H, A, B, C \$KBP\$7\$F X \$,B8:_\$7\$(\$J\$\$NN0h\$,\$o\$+\$k (?^ 8). BP>N@-\$KCm0U\$7, A, B, C \$N F~\$149\$(\$r9MN8\$9\$1\$P, \$3\$1\$i\$N%N!<%I\$K4X78\$9\$kJ,3d \$OA4\$F<!\$N>l9g\$KJ,\$1\$i\$1\$k. \$J\$*, 0J2<\$G\$O A, B, C \$KBP\$7\$F X \$NB8:_\$9\$kNN0h\$r R_X \$GI=\$9.



?^ 7: 3 DN%N!<%IKhCFDj5A5l$kNN0h



?^ 8: 3 E@@)Ls

1. A, B, C $,F1$8B&$K4^$^lkH-

   X $, A, B, C $HF1$8B&$K4^$^lkH-, X $N0LCV $K4X$9$k@)Ls$OF@il$J$$. X $, A, B, C $NH?BP B&$K4^$^$lkH$- (?^ 8(1)), X $ONN0h 111 $KB8:_ 7J$$. 9JoA R_X $O

   001, 010, 011, 100, 101, 110

   $N$$$:l+G"$k.

2. A $H B, C $KJ,$+lkH-

   X $, A $HF1$8B&$K4^$^lkH- (?^ 8(2)), X $ONN0h 011 $KB8:_$7$J$$. 9JoA R_X $O

   001, 010, 100, 101, 110, 111

   $N$$$:l+G"$k.

   X $, B, C $HF1$8B&$K4^$^lkH- (?^ 8(3)), X $ONN0h 100 $KB8:_$7$J$$. 9JoA R_X $O

   001, 010, 011, 101, 110, 111

   $N$$$:l+G"$k.

4QB,$r7+$jJV$7, F@$il?%N!<%I$NJ,3d$+$iJ#?t$N 3 E@@)Ls$rF@$k3H$G, <!Bh$K X $NB8:_$9$kNN0h$rFCDj 7F$$$/3H$,$G$-$k.

3.3 ?7$?$J%N!<%I$NJ,3d$N3MF@Kh$k@)Ls EAGE

0J>eNh$&$K7FF@il$? 3 E@@)Ls$rbHK7$F?7 $?$J%N!<%I$NJ,3d$r3MF@$7, @)Ls$rEAGE5;k3H,$G $-$k.

3 E@@)LsKhCF, 3 DN%N!<%I A, B, C KBP7$F3F %N!<%I$NB8:_9kNN0h$,J,$+CF$$$kH-, 3liN$& AG0U$N 2 DN%N!<%IrDLkD>@~Khk=$NB>$N%N!< %I$NJ,3d$r<!Nh$&$K7F5aak3H$,$G$-$k.

2 DN%N!<%I$N<h$jJ}$O, BP>N@-$KCm0U9k$H?^ 9 $K <($9 15 DLj,$"$k. ?^$NGr4]$OD>@~NDLk 2 DN%N!< %I$rI=$9. 3liN 2 DN%N!<%IrDLkD>@~KhCF, $=$NB>$N%N!<%I$O?^Nh$&$KNN0h **X** $KB8:_$9$k%N!<%I $HNN0h **Y** $KB8:_$9$k%N!<%I$KJ,3d5l$k. $3$3$GNN0h **X**, **Y** KO, Gr4]$GI=$5l?%N!<%IHJCF$$$J$$, GK @~$N8rE@>e$K$"$k 3 DN%N!<%I A, B, C $b4^$^lk.

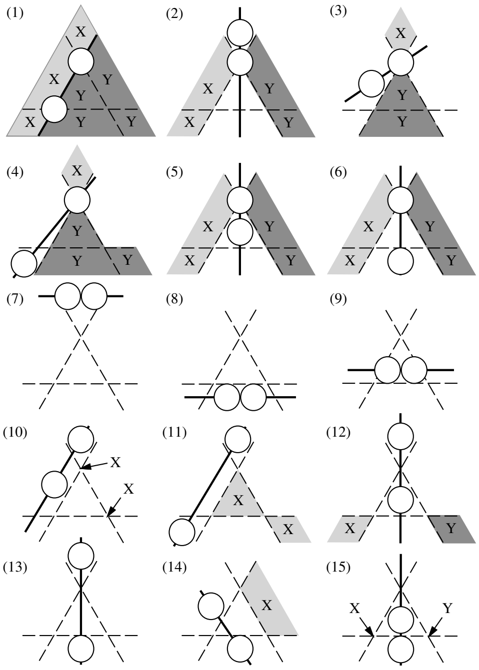
D>@~$, A, B, C N&AN 2 DN%N!<%IrDLk>l9g $,?^ 9(1), A, B, C N&AN 1 DN%N!<%I$H3FNN0h $KB8:_$9$k%N!<%I$rDL$k>l9g$, (2) !A (6), F1$8NN0h$K B8:_9k 2 DN%N!<%IrDLk>l9g$, (7) !A (9), 0[$J$k NN0h$KB8:_9k 2 DN%N!<%IrDLk>l9g$, (10) !A (15) G"$k. J*, (7), (8), (9), (13) $N>l9g$OM-8z$JJ,3d$, J/, (10), (11), (14) $N>l9g$O **X** $G<($5lk%N!<%I$, D>@~$KBP7FF1$8B&$K$"$k3H$r<($7$F$$$k.

3Nh&K7$F5a$a$?J,3d$K$OD>@~$,DL$k 2 DN %N!<%I<+?H$O4^$^lF$$$J$$$,, 5iK=li$N%N!<%I $r4^$`J,3d$r5a$ak3H,G-$k. Nc$($PD>@~ AB $K hC$FNN0h **X** $H **Y** ($K4^$^$l$k%N!<%I) $KJ,3d$5lk >l9g, A, B $N6aK5$rDL$kD>@~$r9M$($l$P,

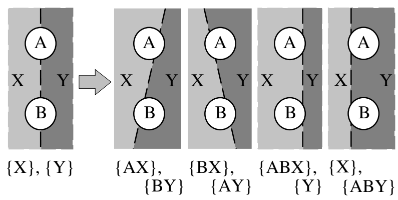
1. {A**X**}, {B**Y**}
2. {B**X**}, {A**Y**}
3. {AB**X**}, {**Y**}
4. {**X**}, {AB**Y**}

$N 4 DNJ,3d$,2DG=G"$k (?^ 10).

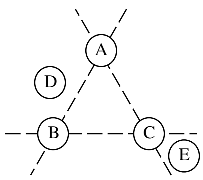
3Nh&K7$F, %N!<%I$NJ,3dKhCFF@il$? 3 E@ @)Ls$+$i?7$?$J%N!<%I$NJ,3d$r3MF@$9k3H,G-$k. 3l$+ibHN 3 E@@)LsHO0[Jk 3 E@@)Ls$rF@k3 H,G-, @)Ls$rEAGE5;$k3H$,G-$k.



?^ 9: 2 DN%N!<%I$N0LCV4X78$HJ,3d



?^ 10: D>@~$,DL$k 2 DN%N!<%I$r4^$`J,3d

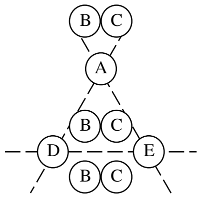


?^ 11: F@il$F$$$k@)Ls$NNc

3.4 @)LsEAGE$NNc

NcH7$F, ?^ 11 Nh$&$K A, B, C KBP9$k D, E $N0LCV$N@)Ls$,F@$ilF$$$k>l9g$K?7$?$J%N!<%I$N J,3d$r5a$a, @)Ls$rEAGE$5$;$k<j=g$r0J2<$K<($9.

$^$:D>@~ AB Kh$k%N!<%I$NJ,3d$r5a$a$k. 3l$O ?^ 9(1) $N>l9g$KAjEv$7, $\boldsymbol{X}$ KO D $,4^$^$l, $\boldsymbol{Y}$ KO C, E $,4^$^lk. =>CF, D>@~ AB KhCF D H CE $KJ,3d2DG=$G$"$k. 5iK3l+$i



?^ 12: EAGE7?@)Ls

$$\{AD\}, \{BCE\}$$
$$\{BD\}, \{ACE\}$$
$$\{ABD\}, \{CE\}$$
$$\{D\}, \{ABCE\}$$

$N 4 DL$j$NJ,3d$,F@il$k.

A !A E N&AG0U$N 2 DN%N!<%IrDLkD>@~$NA*$S J}O_5C_2 = 10$ DLj"$j, $=$l$>$l$N>l9g$K$D$$$FF1MM K7$FJ,3d2DG=$J%N!<%INAHr5aak$H, 0J2<$N 7 DL$j $NJ,3d$,F@il$k.

$\{ABCD\}, \{E\}$	$\{ACE\}, \{BD\}$
$\{ABCE\}, \{D\}$	$\{AD\}, \{BCE\}$
$\{ABD\}, \{CE\}$	$\{AE\}, \{BCD\}$
$\{ACD\}, \{BE\}$	

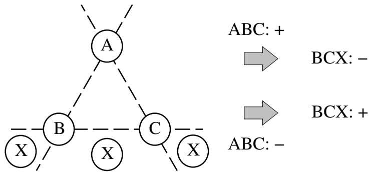
3liNJ,3d$+$iNc$($P 3 DN%N!<%I A, D, E $KBP 7F$O, ?^ 12 Nh$&$J 3 E@@)Ls$,F@$i$l, B, C $NB8:_ 7&$kNN0h$r5aak3H$,G-$k. 9JoA A, B, C KBP9$k D, E $N0LCV$N@)Ls$, A, D, E KBP9$k B, C $N0LCV$N@)Ls$KEAGE$7$F$$$k.

3NNcGO, bH$N 3 E@@)Ls$G$O3F%N!<%I$NB8:_9k NN0h$, 1 DK7hDj5l$F$$$k$,, <B:]$K$OJ#?t$NNN0h$K B8:_$7$&$k$H$$$&@)Ls7+F@il$F$$$J$$>l9gb"$k. 7+7=$N>l9gGb?^ 9 $rMQ$$$FJ,3d$r5a$a, @)Ls$rEA GE$5$;$k3H$,$G$-$k. <!@a$N%7%_%e%l!<%7%g%s<B83$G O3Nh$&$J@)LsEAGE$b9T$C$F$$$k.

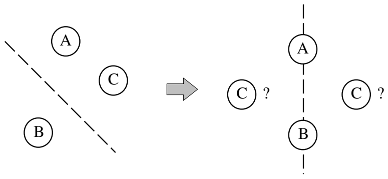
3.5 Dj@-E*6u4V%b%G%kXNJQ49

F@il$? 3 E@@)Ls$KhC$F, %N!<%I X $NB8:_$9$kNN 0h$, 3 DN%N!<%I A, B, C N&$A 2 DrDL$kD>@~$KBP 7FFCDj$NJ}8~$KJk3H$,J,$+lP, A4BNH7$F<B:] $N%N!<%I$N0LCV4X78KBP7$FI=, $^$?$ON"$N$$$:l+$N 4X78$K$"$kDj@-E*6u4V%b%G%k$rF@$k3H$,$G$-$k. $^ $?, $$$:l+ 1 AH$N 3 DN%N!<%I$N0LCV4X78$,M?$(il $F$$$l$P, Dj@-E*6u4V%b%G%k$OM#0l$K7hDj$G$-$k.

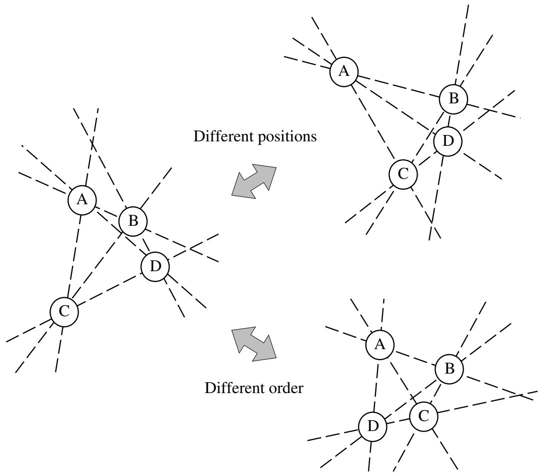
Nc$($P?^ 13 Nh$&$J 3 E@@)Ls$,F@$ilF$$$kH-, A, B, C $N0LCV4X78$, ABC : + G"k3H,J,$+$C $F$$$l$P BCX : − HJ$j, ABC : − G"k3H,J, $+$C$F$$$l$P BCX : + HJ$k.



?^ 13: Dj@-E*6u4V%b%G%kXNJQ49



?^ 14: 2 E@Kh$kI=8=



?^ 15: 4 E@Kh$kI=8=

3.6 9M;!

Dj@-E*6u4V%b%G%kOG0U$N 2 DN%N!<%IKhCF:nil$kD>@~$KBP7F3F%N!<%I$NB8:_9kJ}8~$rI=8=9k. 3N6u4V%b%G%kK*1k@)Ls$O, 3 DN%N!<%I$K8Bi:0lHL$K n 8D$N%N!<%I ($n \geq 2$) N&AG0U$N 2 DrDL$kD>@~rAH_9go;$FI=8=9k3H$b2DG=G"$k.

- 2 DN%N!<%IKh$kI=8=!' 2 DN%N!<%IKhCF 2 DNNN0h$,Dj$^$j, $=$l$>$l$KB8:_$9$k%N!<%I$,<(5l$k. 7+$7$3$NI=8=GO, ?^ 14 Nh$&$K4QB,KhCFF@il$k@)Ls$+$i3F%N!<%I$NB8:_NN0h$rFCDj$9k3HOG-$J$$.
- 3 DN%N!<%IKh$kI=8=!' 3 DN%N!<%IKhCF 7 DNNN0h$,Dj$^$j, 3 E@@)Ls$KhC$F4QB,$KhC$FF@$il?@)Ls$+$iMF0W$K3F%N!<%I$NB8:_9kNN0h$rFCDj$9k3H,G-$k.
- n 8D$N%N!<%I ($n \geq 4$) Kh$kI=8=!'%N!<%I$N0LCVdJBV=g=x$,JQ2=$9kH, $=$lKhCFDj$^$kNN0h$bB?MM$KJQ2=9k (?^ 15). =>CF, 4QB,KhCFF@il$k@)Ls$+$i3F%N!<%I$NB8:_9kNN0h$rFCDj$9kN$O:$FqG"$k.

4 $D0J>e$N%N!<%INAH_9go;$GI=8=$5l?@)Ls$O, 3 E@@)Ls$NAH$_9g$o$;$GI=8=G-$k. =>$C$F, 3 E@@)Ls$O4QB,KhCFF@il$k@)Ls$rDj@-E*6u4V%b%G%kK*1k@)Ls$KJQ49$G$-$k:G$bC1=c$J@)LsG"kH8@$($k.

4 J,;6;k3P%7%9%F%`XN1~MQ

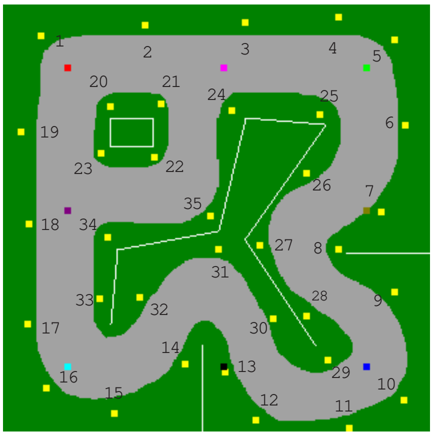
4.1 35MW

J,;6;k3P%7%9%F%`[5](?^ 16) $O<B4D6-$KKd$a9~$^$l$?B??t$N;k3P%;%s%5, $*$h$S$=$l$i$r@\B3$9$k%M%C%H%o!<%/$K$h$C$F9=@.$5$l$?%7%9%F%`G"$k. 3N%7%9%F%`$O4D6-$r;k3PE*$KG'<1$7, MM!9$J>pJs$rJ,@O, Ds6!$9$k$b$N$G$"$k$,, %7%9%F%`$,3F;k3P%;%s%5$N0LCV4X78rCNC$F$$$l$P, ?M$d%m%\%C%HJI$NMxMQ<T$X$N>pJsDs6!$K$*$$$FM-MxG"$k.

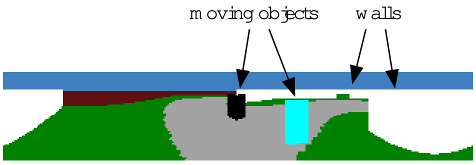
?^ 16: J,;6;k3P%7%9%F%` — 39%b%G%k

3l$^$G$K=R$Y$?Dj@-E*6u4V%b%G%k$N3MF@<jK!$r, 3NJ,;6;k3P%7%9%F%`K*1k;k3P%;%s%5$NDj@-E*$J0LCV4X78$N3MF@$K1~MQ$7, %7%_%e%l!<%7%g%s$r9TC?. %7%_%e%l!<%7%g%s4D6-$O<!$NH*jG$"$k.

- $30\mathrm{m} \times 30\mathrm{m}$ $NJ?LL>e$K 35 Bf$N;k3P%;%s%5$H 8 DN0\F0J*BN$,B8:_$9$k (?^ 17). ?^$NGr$$@~$O;kLn$r<WkJIG$"$k.
- 0\F0J*BN$OF;O)>e (?^$NGv$$3%?'$NNN0h) $r $10\mathrm{cm/step}$ (1 step $O%7%_%e%l!<%7%g%s$N:G>.;~4VC10L) $NB.$5$G%i%s%@%`%&%)!<%/$9$k.
- 3F;k3P%;%s%5$OA4J}0L;k3P%;%s%5$G$"$j, $"$ifkJ}8~$KB8:_$9$kJ*BN$r4QB,9k3H$,$G$-$k. %;%s%5$N3QEYJ,2rG=$OL58BG"$j, J*BN$N0\F0J}8~$r8m$jJ/8!=P9k3H$,$G$-$k$,, %;%s%5$+$iLs



?^ 17: %7%_%e%l!<%7%g%s4D6-



?^ 18: A4J}0L;k3P%;%s%5KhCFF@il$k2hA|

10m 0J>eN%1?J*BN$r8!=P$9k3HOG-$J$$. ?^ 18 $O, ?^ 17 $N;k3P%;%s%5 14 KhCFF@il$?2hA|$NNcG"$k.

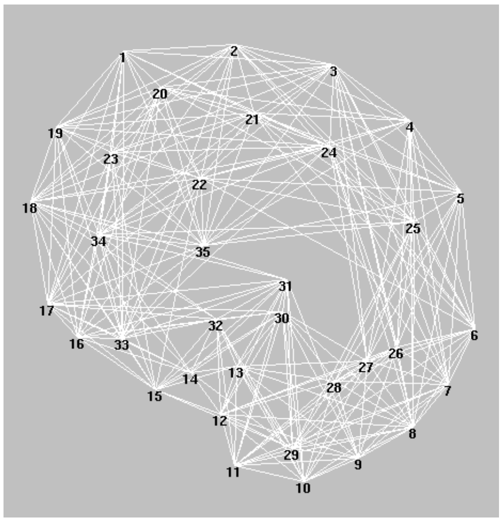
J*@)LsEAGE$K4X$7FO, ?^ 9 $K<($7$?J,3d$N$&$A (7) !A (15) $NJ,3d$OJ#;($G7W;;NL$,B?$$$N$G, 3N%7%_%e%l!<%7%g%sK*$$$F$O (1) !A (6) $NJ,3d$N$_$rMQ$$$?.

4.2 <B837k2L

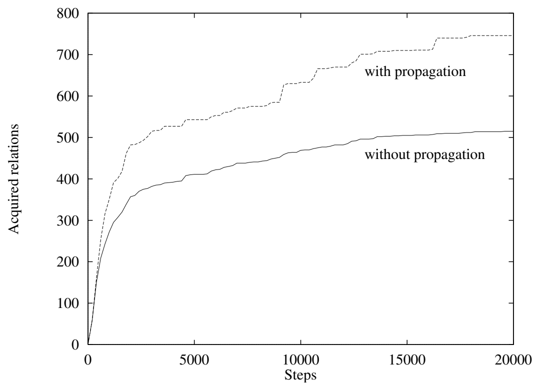
?^ 19 $O%7%_%e%l!<%7%g%s$r3+;O7F$+$i 20,000 step 8e$KF@$il?%N!<%I (;k3P%;%s%5) $N0LCV4X78$K4p$E$$$F, IUO?$K<($9<jK!KhCFIA$$$?bNG"$k.

?^ 20 $N with propagation $O7hDj$5l?%N!<%I$N0LCV4X78$N?t$N?d0\$G$"$k. $^$?, @)LsEAGE$rMQ$$$J$$$C$?>l9g$r without propagation H7$FF1?^$K<(7F$$$k. 2#<4$O step ?t, =D<4$O7hDj5l$?0LCV4X78$N?t$rI=$9.

3N%7%_%e%l!<%7%g%sGO0LCV4X78$NAm?t, 9JoA 3 DN%N!<%INAH_9go;$NAm?t$O $_{35}C_3 = 6545$ AHG"$k. @)LsEAGE$rMQ$$$:$K7hDj$9k3H,G-kN$O;~$KJ*BN$r4QB,$G$-$k%N!<%I$N0LCV4X78$N$_$G$"$j, 3l$r9MN8$7$?>l9g$O7hDj2DG=$J0LCV4X78$N?tO*h= 540 AHHJ$k. ?^ 20 Nh$&$K, @)LsEAGE$rMQ$$$J$+$C$?>l9g$O3liN$&$AN[HsIG$"$k 515 AH$N0LCV4X78$,7hDj5l$F$$$k. $^$?, @)LsEAGE$rMQ$$$?>l9gO3lrBg$-$/>e2s$k 746 AH$N0LCV4X78$,7hDj$5lF$$$k.



?^ 19: ;k3P%;%s%5$NDj@-E*0LCV4X78



?^ 20: 7hDj5l$?0LCV4X78$N?t

3Nh&$K, K\<jK!$KhC$F, 4QB,$KhC$FD>@\7hDj2DG=$J%N!<%I$N0LCV4X78$N$[$HsI$r7hDj$9k3H,G-$?. $^$?@)LsEAGE5;k3HKhC$F, %;%s%5$N<kLnJI$N@)8B$rD6$($F5i$KB?$/$N0LCV4X78$r7hDj9k3H$,$G$-$?.

5 $*$ojK

J#?t$N%i%s%I%^!<%/$H$=$N4V$r0\F0$9$kJ*BN$N1?F0HN4X78$r4QB,$7, 4v2?E*$J@)Ls$G$"$k 3 E@@)LsrE,MQ7, @)Ls$rEAGE$5$;$k3HKhCFDj@-E*6u4V%b%G%k$r3MF@$9$k<jK!$rDs0F7?. $^$?, J,;6;k3P%7%9%F%`K*1k;k3P%;%s%5$NDj@-E*$J0LCV4X78$r3MF@$9$k%7%_%e%l!<%7%g%s$KhC$F, 3N<jK!$,M-8zG"$k3H$r<(7?.

:#8e$N2]Bj$H7F, 4QB,7?J*BN ($^$?$O%N!<%I) $NBP1~$N8mjr9MN8$9$kI,MW$,$"$k. 8=:_$OBP1~$N8m$jOJ$$$bNH7Fk,, FC$K%;%s%5$H7F;k3P%;%s%5$rMQ$$$?%7%9%F%`GOBP1~$N8m$j$OIQHK$K5/$-$k2DG=@-$,

$"$k. 3N>l9g$O 3 E@@)Ls$rE,MQ9k:]$KL7=b$,5/3k $?$a, E,@Z$JBP1~$r5aaF@)LsrE,MQ7D>$9<jK!$,I,MW HJ$k.

;29MJ88%

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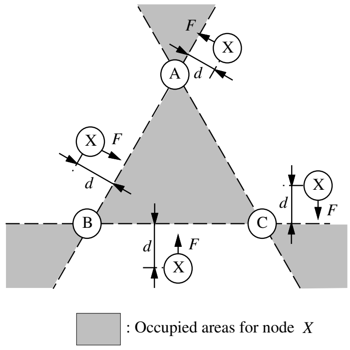
IUO? 3 E@@)Ls$K4p$E$/%N!<%I$N0LCV4X78$N I=<(

G$0U$N 3 DN%N!<%IH=$NB>$N%N!<%I$N0LCV4X78$K 4pE/%N!<%I$NDj@-E*$J0LCV4X78$NI=<($O, 0J2<$K<($9 <jK!KhCF9TC?.

1. A4FN%N!<%IrE,EvKG[CV9k.
2. $"$k 3 DN%N!<%I A, B, C K*$$$F, %N!<%I X $r L7=b$N$J$$NN0h$K0\F0$5$;$kNO $\boldsymbol{F}$ $r<!$Nh&K7 $F5a$a$k.
   - X $,L7=b$7$?NN0h$K$"$kH-, $\boldsymbol{F}$ $O:G$b6a$$, L7=bNJ$$NN0h$K8~$+$&NO$H$7, $=$NNN0h$^ GN5wN%$r d H7$?$H$-, $|\boldsymbol{F}| \propto \exp(d)$ H9 $k (?^ 21).
   - X $,L7=b$N$J$$NN0hK"kH$-, $\boldsymbol{F}$ O=$NNN 0h$NCf?4$K8~$+$&NO$H9k.
3. G$0U$N 3 DN%N!<%IKBP9$k0LCV4X78$rbH$K X $KF/$/NO$r5a$a, $=$N9gNO$K4p$E$$$F X $rHy>.$K 0\F0$5$;$k.
4. $=$NB>$N%N!<%I$K$D$$$F$b 2., 3. $N<j=g$G0\F0$5 $;$k.



?^ 21: %N!<%I X $KF/$/NO F

5. A4FN%N!<%I$N0LCV$,Dj$^$k$^$G 2., 3., 4. $r7+$j JV$9. C"$7, %N!<%I$,L7=b$7$?0LCV$K$"$k>uBV$G6I =j:GE,2r$K4Yk3H,$"$kNG, $=$N>l9g$O?M4V$, 2pF~$72sHr$9$k.