



IJCAI 87

**PROCEEDINGS OF THE TENTH INTERNATIONAL
JOINT CONFERENCE ON ARTIFICIAL INTELLIGENCE**
MILAN • AUGUST 23-28, 1987



Petitioner has added romanettes to pages (a) and (i) - (ii). Otherwise, it leaves the original page numbering.

VOLUME 2

**MICROSOFT CORP.
EXHIBIT 1023**

(a)

IJCAI 87

**Proceedings of the
Tenth International Joint Conference
on
Artificial Intelligence**

Volume 2

August 23-28, 1987

sponsored by

**International Joint Conferences on
Artificial Intelligence, Inc. (IJCAI)**

cosponsored and hosted by

**Associazione Italiana per l'Informatica ed
il Calcolo Automatico-A.I.C.A.**

(Gruppo di Lavoro di Intelligenza Artificiale GLIA)

in cooperation with

Politecnico di Milano, Italy

Copyright © 1987. International Joint Conferences
on Artificial Intelligence, Inc.
All rights reserved.

Edited by
John McDermott

Distributed by
Morgan Kaufmann Publishers, Inc.
95 First Street
Los Altos, California 94022

ISBN 0-934613-43-5

Printed in the Netherlands
through Interprint, San Francisco.

87011184

Contents

Volume 1

Artificial Intelligence Conference Proceedings Ordering Information	iv
IJCAI-87 Supporters	v
Conference Organization	vii
Referees	ix
Awards, Speakers, and Panels	xi
Conference Schedule	xiii
Organization of Papers	xv
Proceedings Papers	1
Architectures and Languages	1
Cognitive Modeling	105
Knowledge Acquisition	193
Knowledge Representation	365
Author Index	600

Volume 2

Artificial Intelligence Conference Proceedings Ordering Information	iv
IJCAI-87 Supporters	v
Conference Organization	vii
Conference Schedule	ix
Organization of Papers	xi
Proceedings Papers	601
Natural Language	601
Perception	727
Reasoning	859
Robotics	1119
Panels and Invited Talks	1161
Author Index	1193

Author Index

- Adorni, G., 775
 Afshartous, N., 380
 Aikins, J., 1165
 Allemang, D., 1112
 Allen, J., 981
 Aloimonos, J., 738, 815
 Andersen, S., 366
 Andreassen, S., 366
 Appelt, D., 640
 Araya, A., 552
 Arbab, B., 1145
 Arens, Y., 688
 Arik, Y., 783
 Asada, M., 797
 Ayache, N., 808, 826
- Baker, M., 185
 Ballim, A., 118
 Banerji, R., 280
 Barbuceanu, M., 563
 Barnard, S., 832
 Barron, J., 822
 Basu, A., 815
 Baykan, C., 1035
 Bena, C., 576
 Benanav, D., 973
 Benjamin, D.P., 256
 Bennett, S., 239
 Bhanu, B., 819
 Bhatnagar, N., 249
 Bibel, W., 1162
 Binford, T., 759
 Binot, J.-L., 709
 Black, D., 87
 Blelloch, G., 323
 Blicher, A.P., 767
 Boguraev, B., 703
 Bonissone, P., 891
 Bonzon, P., 18
 Bookman, L., 380, 611
 Bouissou, M., 541
 Bowen, J.B., 1138
 Bozinovic, R., 844
 Brayshaw, M., 83
 Breuker, J., 167
 Brewka, G., 483
 Briot, J.-P., 40
 Briscoe, T., 703
 Brown, C., 779
 Brown, Jr., A., 973
 Burger, W., 819
 Burns, J.B., 763
 Burstein, M., 185
 Bylander, T., 1112
- Caloud, P., 1086
 Carbonell, J., 228, 718
 Carroll, J., 703
 Chalfan, K., 592
 Chandrasekaran, B., 1183
 Chen, K.J., 619
 Chen, S., 742
 Cheng, J., 1018
 Chiu, C., 1079
- Chou, P., 779
 Chun, H., 380
 Cohen, P., 100
 Cointe, P., 40
 Collinot, A., 1032
 Collins, A., 185
 Connell, J., 1124
 Crowley, J., 793
 Cunningham, P., 443
- Dahlgren, L., 446
 Danyluk, A., 274
 Davies, T., 264
 Davis, R., 1071
 Dayantis, G., 9
 de Haas, L.J., 790
 de Mori, R., 840
 de Rougemont, M., 993
 Dean, T., 860
 Decker, K., 891
 DeJong, G., 205, 236
 Delgrande, J., 315, 423
 Di Eugenio, B., 648
 di Martino, J., 836
 Diederich, J., 201
 Dreschler-Fischer, L., 749
 Driankov, D., 899
 Dubois, D., 984
 Durfee, E., 875
 Dyer, M., 147, 277, 696
- Eisenstadt, M., 83
 Elio, R., 293
 Emde, W., 209
 Ensor, J.R., 682
 Epstein, S., 194
 Etherington, D., 489, 495
- Falck, B., 366
 Falkenhainer, B., 260
 Faltings, B., 430, 436
 Farrell, R., 174
 Faugeras, O., 808, 1166
 Faverjon, B., 1131
 Feigenbaum, E., 1172
 Finin, T., 559
 Fischer, G., 177
 Fisher, R., 805
 Fleck, M., 728
 Flowers, M., 277, 696
 Forbus, K., 409, 430
 Fox, M., 1035
 Freedman, R.S., 939
 Freudenstein, D., 801
 Frisby, J.P., 1138
 Frisch, A., 515
 Fronhofer, B., 15
- Ganascia, J.-G., 345
 Gans, S., 891
 Gaucas, D., 973
 Gazdar, G., 1172
 Geffner, H., 1105
 Geiger, D., 745
- Geller, J., 545
 Genesereth, M., 416
 Gergely, T., 932
 Gershon, R., 752, 755
 Ghislanzoni, R., 44
 Glicksman, J., 1047
 Gnutzmann, F., 749
 Golding, A., 334
 Granacki, Jr., J., 688
 Grishman, R., 692
 Grover, C., 703
 Gruber, T., 100
 Guesgen, H.W., 30
 Guggenheimer, H., 939
 Guo, C., 715
 Gupta, A., 524
- Haas, A., 615
 Haddock, N., 661
 Hammond, K., 109
 Hanson, A., 811
 Hartman, L., 535
 Hasida, K., 664
 Haugh, B., 449
 Hayes, P., 981
 He, Z., 91
 Healey, G., 759
 Hein, H.-W., 97
 Hendler, J., 151
 Hill, W., 338
 Hirschberg, J., 636
 Hirsh, H., 221
 Hobbs, J., 520
 Hodges, J., 696
 Hoenkamp, E., 115
 Horthy, J., 476
 Hsiang, J., 990
 Hsu, C.-C., 62
 Huang, J., 619
 Hull, J., 848
 Hummel, R., 1015
- Iberall, T., 1153
 Iline, H., 34
 Imielinski, T., 997
 Immovilli, M., 775
 Irani, K., 1018
 Isizaki, S., 664
- Jackson, P., 942
 Jacobs, P., 675
 Jappinen, H., 700
 Jensen, K., 709
 Jepson, A., 752, 755, 822
 Johnson, B., 1164
 Jones, M., 602
 Josephson, J., 1112
 Junker, U., 30
- Kahn, G., 355, 531
 Kakusho, O., 359
 Kanoui, H., 34
 Kawaguchi, A., 359
 Kellerman, G., 97
- Kempen, G., 655
 Kender, J., 801
 Kitchen, L., 763
 Klein, D., 559
 Kodratoff, Y., 271, 348
 Kohl, C., 811
 Konolige, K., 394
 Koseki, Y., 76
 Krishna, G., 214
 Kronfeld, A., 640
 Ksiezyk, T., 692
 Kuipers, B., 1079
 Kumar, K., 472
 Kyburg, H., 902
- Ladkin, P., 462
 Laird, J., 334
 Lakemeyer, G., 402
 Lang, J., 984
 Langley, P., 198
 Laumond, J.-P., 1120
 Lavin, M., 1149
 Le Pape, C., 1032
 Lee, L., 619
 Lehtola, A., 700
 Lenat, D., 1172
 Lesmo, L., 648
 Lesser, V., 875
 Letovsky, S., 512
 Leyton, M., 771
 Lifschitz, V., 966
 Linden, T., 1047
 Lippolt, B., 1157
 Litman, D., 636
 Lowry, M., 1004
 Luria, M., 1025
 Lustman, F., 826
- Mackenzie, H., 584
 Malik, J., 734
 Manago, M., 348
 Manevitz, L., 1015
 Manley, J., 87
 Margolis, N., 362
 Marsland, T.A., 951
 Martin, J., 137
 Martin, P., 520
 Massone, L., 775
 Mathonet, R., 527
 Matsumoto, Y., 671
 Mayhew, J.E.W., 1138
 McCluskey, T.L., 331
 McDowell, J., 446
 McKeown, K., 682
 McKevitt, P., 569
 Merlo, E., 840
 Miller, D., 1067
 Miller, M., 499
 Minton, S., 228
 Mittal, S., 552
 Mizoguchi, R., 359
 Moerdler, G., 682
 Molnar, B., 563
 Montini, G., 68, 576

Morgenstern, L., 867
Morimoto, M., 783
Mostow, J., 249, 1090
Muggleton, S., 287
Mukerjee, A., 472
Mulder, J., 855
Murray, K., 297
Murray, T., 189
Murty, M.N., 214
Muscettola, N., 1063

Natarajan, K.S., 955
Nguyen, V-D., 787
Nielsen, P., 430
Nordhausen, B., 198
Nutter, J., 373

O'Brien, C., 596
Ortony, A., 106

Palakal, M., 840
Paris, C., 626
Parker, A., 688
Partridge, D., 106
Pazzani, M., 147, 277
Pearl, J., 1105
Pepper, J., 531
Perlis, D., 163, 499
Peters, S., 140
Pierrehumbert, J., 636
Pinson, S., 588
Poesio, M., 622
Poggio, T., 745
Pollard, S.B., 1138
Poole, D., 905
Porrill, J., 1138
Prade, H., 984
Pridmore, T.P., 1138

Quinlan, J.R., 304
Rajamoney, S., 205
Ratcliffe, M., 48
Rau, L., 155
Raulefs, P., 468
Reichgelt, H., 942
Reinefeld, A., 951
Reinstein, 1164
Rendell, L., 308
Riseman, E., 811
Rosenberg, C., 323
Rosenbloom, P., 334
Rouat, J., 840
Ruizhao, Y., 945
Rullent, C., 622
Rusinowitch, M., 990
Ruspini, E., 924
Russell, S., 264

Sakai, K., 990
Sakai, T., 783
Sandberg, J., 167
Sandewall, E., 1055
Sandini, G., 775
Schaefer, P., 502
Schefer, P., 509
Schoppers, M.J., 1039
Segre, A., 242
Shanahan, M., 987
Shapiro, S., 140, 545
Shastri, L., 851
Shavlik, J., 236
Shekar, B., 214
Sheshu, R., 308
Shoham, Y., 388
Silverman, G., 1149
Simmons, R., 1071
Singer, M., 829

Sirovich, F., 576
Slack, M., 1067
Sleeman, D., 1166
Smith, S., 1063
Spampinato, L., 44
Srihari, S., 844, 848
Stanton, R., 584
Steier, D., 327
Stepp, R., 211
Sterling, J., 692
Strat, T., 1097
Subramanian, D., 416
Sugimura, R., 671
Syre, J-C., 48
Szabo, ZS., 932

Tanner, M., 1112
Tao, Y., 945
Tcheng, D., 308
Tecuci, G., 271
Tenenberg, J., 535, 1011
Thomas, C., 97
Thomason, R., 476
Thornton, C., 301
Tomabeche, H., 722
Tomita, M., 718
Tong, X., 91
Tornielli, G., 44
Touretzky, D., 476
Tournassoud, P., 1131
Trausan-Matu, S., 563
Tsai, R., 1149
Tsang, E., 456
Tseng, C., 619
Tsotsos, J., 752, 755, 822
Tsui, S., 731, 1127

Valkonen, K., 700
van Biema, M., 56

Van Cotthem, H., 527
van Hentenryck, P., 2
Vanryckeghem, L., 527
Velthuisen, H., 1157
Veronis, J., 633
Villatte, N., 541
Voigt, K., 1090
Vonk, J., 1157
Voss, A., 30

Wahlster, W., 1162
Wallen, L., 917
Ward, G., 636
Watanabe, L., 293
Watrous, R., 851
Weld, D., 959
Wellman, M., 884
Wilks, Y., 118, 569
Wilson, S., 217
Winkels, R., 167
Woldbye, M., 366
Wolstenholme, D., 596
Woolf, B., 189
Wu, J-J., 62
Wu, S-M., 62

Xu, G., 731

Yamaguchi, T., 359
Yamasaki, S., 24
Yang, Y., 679
Yokomori, T., 283
Yu, R., 91

Zadrozny, W., 909
Zernick, U., 125, 133
Zheng, J., 1127
Zhijun, H., 945

Index

Q 334 .I6 1987x v.2
87-11184
International Joint
Conference on Artificial
IJCAI 87

Learning Resources
STATE UNIVERSITY
St. Cloud, MN 56301

Adorni
Afshar
Aikins,
Alleman, J., 981
Allen, J., 981
Aloimonos, J., 738, 815
Andersen, S., 366
Anderson, J.

Comrie, J.
Collins, A., 185
Connell, J., 1124

Geller, J., 545
Genesereth, M., 416
Gergely, T., 932
Gershon, R., 752, 755
Ghislanzoni, R., 44
Glicksman, J., 1047

Kempen, G., 655
Kender, J., 801
Kitchen, L., 763
Klein, D., 559
Kodratoff, Y., 271, 348
Kohl, C., 811
Konolige, K., 394
Koseki, Y., 76
Krishna, G., 214
Kronfeld, A., 640
Ksiezyk, T., 692
Kuipers, B., 1079
Kumar, K., 472
Kyburg, H., 902

Date Due

App					
Aray					
Arb					
Arer					
Ariki					
Asac					
Ayac	DEC 8 1988				
Bake					
Ballir	NOV 18 1988				
Bane	OCT 2 1989				
Barbi					
Barna					
Barro	OCT 8 1990				
Basu	JUL 8 1988				
Bayka					
Bena					
Benar					
Benjar					
Benne					
Bhanu					
Bhatna					
Bibel, V					
Binford					

Ladkin, P., 462
Laird, J., 334
Lakemeyer, G., 402
Lang, J., 984
Langley, P., 198
Laumond, J-P., 1120
Lavin, M., 1149
Le Pape, C., 1032
Lee, L., 619
Lehtola, A., 700
Leinat, D., 1172
Lemo, L., 648
Lisser, V., 875
Litovsky, S., 512
Lyton, M., 771

Cat No. 23 231

Printed in U.S.A.

Lifschitz, V., 966
Linden, T., 1047
Lippolt, B., 1157
Litman, D., 636
Lowry, M., 1004
Luria, M., 1025
Lustman, F., 826

Binot, J-L., 709
Black, D., 87
Blelloch, G., 323
Blicher, A.P., 767
Boguraev, B., 703
Bonissone, P., 891
Bonzon, P., 18
Bookman, L., 380, 611
Bouissou, M., 541
Bowen, J.B., 1138
Bozinovic, R., 844
Brayshaw, M., 83
Breuker, J., 167
Brewka, G., 483
Briot, J-P., 40
Briscoe, T., 703
Brown, C., 779
Brown, Jr., A., 973
Burger, W., 819
Burns, J.B., 763
Burstein, M., 185
Bylander, T., 1112

Eisenstadt, M., 83
Elio, R., 293
Emde, W., 209
Ensor, J.R., 682
Epstein, S., 194
Etherington, D., 489, 495

Fischer, J., 636
Hirsh, H., 221
Hobbs, J., 520
Hodges, J., 696
Hoenkamp, E., 115
Horty, J., 476
Hsiang, J., 990
Hsu, C-C., 62
Huang, J., 619
Hull, J., 848
Hummel, R., 1015

Mackenzie, H., 584
Malik, J., 734
Manago, M., 348
Manevitz, L., 1015
Manley, J., 87
Margolis, N., 362
Marsland, T.A., 951
Martin, J., 137
Martin, P., 520
Massone, L., 775
Mathonet, R., 527
Matsumoto, Y., 671
Mayhew, J.E.W., 1138
McCluskey, T.L., 331
McDowell, J., 446
McKeown, K., 682
McKevitt, P., 569
Merlo, E., 840
Miller, D., 1067
Miller, M., 499
Minton, S., 228
Mittal, S., 552
Mizoguchi, R., 359
Moerdler, G., 682
Molnar, B., 563
Montini, G., 68, 576

Falck, B., 366
Falkenhainer, B., 260
Faltings, B., 430, 436
Farrell, R., 174
Faugeras, O., 808, 1166
Faverjon, B., 1131
Feigenbaum, E., 1172
Finin, T., 559
Fischer, G., 177
Fisher, R., 805
Fleck, M., 728
Flowers, M., 277, 696
Forbus, K., 409, 430
Fox, M., 1035
Freedman, R.S., 939
Freudenstein, D., 801
Frisby, J.P., 1138
Frisch, A., 515
Fronhofer, B., 15

Iberall, T., 1153
Iline, H., 34
Imielinski, T., 997
Immovilli, M., 775
Irani, K., 1018
Isizaki, S., 664
Jackson, P., 942
Jacobs, P., 675
Jappinen, H., 700
Jensen, K., 709
Jepson, A., 752, 755, 822
Johnson, B., 1164
Jones, M., 602
Josephson, J., 1112
Junker, U., 30

Caloud, P., 1086
Carbonell, J., 228, 718
Carroll, J., 703
Chaffan, K., 592
Chandrasekaran, B., 1183
Chen, K.J., 619
Chen, S., 742
Cheng, J., 1018
Chiu, C., 1079

Ganascia, J-G., 345
Gans, S., 891
Gaucas, D., 973
Gazdar, G., 1172
Geffner, H., 1105
Geiger, D., 745

Kahn, G., 355, 531
Kakusho, O., 359
Kanoui, H., 34
Kawaguchi, A., 359
Kellerman, G., 97

- Morgenstern, L., 867
 Morimoto, M., 783
 Mostow, J., 249, 1090
 Muggleton, S., 287
 Mukerjee, A., 472
 Mulder, J., 855
 Murray, K., 297
 Murray, T., 189
 Murty, M.N., 214
 Muscettola, N., 1063

 Natarajan, K.S., 955
 Nguyen, V-D., 787
 Nielson, P., 430
 Nordhausen, B., 198
 Nutter, J., 373

 O'Brien, C., 596
 Ortony, A., 106

 Palakal, M., 840
 Paris, C., 626
 Parker, A., 688
 Partridge, D., 106
 Pazzani, M., 147, 277
 Pearl, J., 1105
 Pepper, J., 531
 Perlis, D., 163, 499
 Peters, S., 140
 Pierrehumbert, J., 636
 Pinson, S., 588
 Poesio, M., 622
 Poggio, T., 745
 Pollard, S.B., 1138
 Poole, D., 905
 Porritt, J., 1138
 Prade, H., 984
 Pridmore, T.P., 1138

 Quinlan, J.R., 304

 Rajamoney, S., 205
 Ratcliffe, M., 48
 Rau, L., 155
 Raulefs, P., 468
 Reichgelt, H., 942
 Reinefeld, A., 951
 Reinstein, 1164
 Rendell, L., 308
 Riseman, E., 811
 Rosenberg, C., 323
 Rosenbloom, P., 334
 Rouat, J., 840
 Ruizhao, Y., 945
 Rullent, C., 622
 Rusinowitch, M., 990
 Ruspini, E., 924
 Russell, S., 264

 Sakai, K., 990
 Sakai, T., 783
 Sandberg, J., 167
 Sandewall, E., 1055
 Sandini, G., 775
 Schaefer, P., 502
 Schefe, P., 509
 Schoppers, M.J., 1039
 Segre, A., 242
 Shanahan, M., 987
 Shapiro, S., 140, 545
 Shastri, L., 851
 Shavlik, J., 236
 Shekar, B., 214
 Sheshu, R., 308
 Shoham, Y., 388
 Silverman, G., 1149
 Simmons, R., 1071
 Singer, M., 829

 Sirovich, F., 576
 Slack, M., 1067
 Sleeman, D., 1166
 Smith, S., 1063
 Spampinato, L., 44
 Srihari, S., 844, 848
 Stanton, R., 584
 Steier, D., 327
 Stepp, R., 211
 Sterling, J., 692
 Strat, T., 1097
 Subramanian, D., 416
 Sugimura, R., 671
 Syre, J-C., 48
 Szabo, ZS., 932

 Tanner, M., 1112
 Tao, Y., 945
 Tcheng, D., 308
 Tecuci, G., 271
 Tenenberg, J., 535, 1011
 Thomas, C., 97
 Thomason, R., 476
 Thornton, C., 301
 Tomabeche, H., 722
 Tomita, M., 718
 Tong, X., 91
 Tornielli, G., 44
 Touretzky, D., 476
 Tournassoud, P., 1131
 Trausan-Matu, S., 563
 Tsai, R., 1149
 Tsang, E., 456
 Tseng, C., 619
 Tsotsos, J., 752, 755, 822
 Tsuji, S., 731, 1127

 Valkonen, K., 700
 van Biema, M., 56

 Van Cotthem, H., 527
 van Hentenryck, P., 2
 Vanryckeghem, L., 527
 Velthuisen, H., 1157
 Veronis, J., 633
 Villatte, N., 541
 Voigt, K., 1090
 Vonk, J., 1157
 Voss, A., 30

 Wahlster, W., 1162
 Wallen, L., 917
 Ward, G., 636
 Watanabe, L., 293
 Watrous, R., 851
 Weld, D., 959
 Wellman, M., 884
 Wilks, Y., 118, 569
 Wilson, S., 217
 Winkels, R., 167
 Woldbye, M., 366
 Wolstenholme, D., 596
 Woolf, B., 189
 Wu, J-J., 62
 Wu, S-M., 62

 Xu, G., 731

 Yamaguchi, T., 359
 Yamasaki, S., 24
 Yang, Y., 679
 Yokomori, T., 283
 Yu, R., 91

 Zadrozny, W., 909
 Zernick, U., 125, 133
 Zheng, J., 1127
 Zhijun, H., 945

A Knowledge Framework for Natural Language Analysis

Paul S. Jacobs

AI Branch, GE Corporate R & D
Schenectady, NY 12301 USA

Abstract

Recent research in language analysis and language generation has highlighted the role of knowledge representation in both processes. Certain knowledge representation foundations, such as structured inheritance networks and feature-based linguistic representations, have proved useful in a variety of language processing tasks. Augmentations to this common framework, however, are required to handle particular issues, such as the *ROLE RELATIONSHIP* problem: the task of determining how roles, or slots, of a given frame, are filled based on knowledge about other roles. Three knowledge structures are discussed that address this problem. The semantic interpreter of an analyzer called TRUMP (TRansportable Understanding Mechanism Package) uses these structures to determine the fillers of roles effectively without requiring excessive specialized information about each frame.

I. Introduction

A variety of work in language analysis [Bobrow and Weber, 1980, Sondheimer *et al.*, 1984, Lytinen, 1984, Hirst, 1987] and language generation [Jacobs, 1985, Sondheimer and Nebel, 1986] exploits some *STRUCTURED* knowledge representation. A structured representation is one in which entities, or *FRAMES*, and their slots, or *ROLES*, may be related to more abstract objects and roles, as in *KL-ONE* [Brachman and Schmolze, 1985], *FRAIL* [Charniak *et al.*, 1983], or *KODIAK* [Wilensky, 1986]. The main advantage of structured representations for natural language is that knowledge about how a given frame or role is expressed linguistically may be taken as default knowledge about the expression of more specific frames and roles.

SEMANTIC INTERPRETATION is the part of the language analysis process that consists of constructing a correct, complete representation of the content of a natural language input. The task is difficult because there are no hard and fast rules about the relationship between linguistic structure and underlying meaning. For example, consider the following inputs:

- (1a) Frank was sent the message by Jones.
- (1b) The message was sent Frank by Jones.
- (1c) The job was sent to the line printer by Jones.

- (2a) How many arguments does the command take?
- (2b) 'Rm' gives you the names of your files.

Sentences (1a-c) illustrate distinct senses of the verb "send", even in the computer domain, as well as the problem of determining the role of Frank in the British English of (1b), structurally identical to (1a). (2a) and (2b) demonstrate metaphorical senses of "take" and "give", metaphorical because a command operating upon arguments is not actively *taking* them, and printing a list of files is not really *giving* because you don't receive anything. Practically, we want to avoid representing the senses as *giving* or *taking* because the other concepts involved violate constraints or *SELECTIONAL RESTRICTIONS* on the roles they would play: Commands are not suited to being *givers* or *takers* as they are not animate. A variety of work in linguistics and AI [Chafe, 1968, Becker, 1975, Wilks, 1978] has argued that metaphors such as these may be the rule as much as the exception.

A major problem in interpreting sentences such as the above is the following:

- *The Role Relationship Problem*: The problem of determining, for a given candidate frame, what the conceptual fillers are of the roles of that frame, given a combination of abstract and specialized linguistic knowledge. In (1a-c) candidate frames are *sending-electronic-mail* and *transmission-to-printing-device*; in (2a) candidates include *command-execution* and *command-producing-output*. The semantic interpreter must determine, for example, that Frank fills the *source* role and Jones the *addressee* of the *sending-electronic-mail* event in (1a) or that the arguments mentioned in (2b) fill the *input* role of the command. This problem is important because it should not be necessary to specify, for each potential frame, the extensive knowledge required to fill the roles of that frame appropriately.

This paper describes how the features of a representation called ACE apply to the problem described above. The representation is used both by the KING generator [Jacobs, 1985] and a language analyzer, TRUMP (TRansportable Understanding Mechanism Package) [Jacobs, 1986], in a variety of applications.

II. The Ace Framework

Ace is a set of tools originally designed to promote extensibility by encoding knowledge about language in a uniform manner (Jacobs and Rau, 1985). As with some of the work with KL-ONE (Bobrow and Webber, 1980, Sondheimer *et al.*, 1984), the idea of Ace is to use the same structured representation, KODIAC (Wilensky 1986), for both linguistic and conceptual structures, but the representation is augmented by having explicit structures that tie together linguistic and conceptual roles.

The discussion that follows considers the Ace knowledge structures used in representing these role relationships and how these structures can be used to determine appropriate role fillers in linguistic processing.

A. Linguistic Relations

Linguistic relations in Ace represent the linguistic structures to which conceptual roles are associated. These relations are organized hierarchically, so that often the syntactic realization of a linguistic relation derives from a more abstract category, while its meaning is represented at a more specific level.

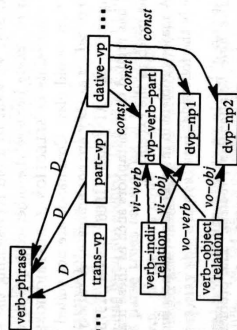


Figure 1: Linguistic relations and syntactic structures

Figure 1 shows the Ace representation of two linguistic relations applicable to the examples discussed here, the "P" link in these figures stands for *DOMINATE*, the KO-DIAK term for subsumption, or "a-k-o". Common relations such as *verb-indir-relation* and *verb-object-relation* are associated with syntactic structures; since these relations might appear in a range of surface forms, the association of linguistic and conceptual information to the relations adds flexibility to the system.

. The REF Association

Linguistic relations provide a hierarchy of linguistic roles that are associated with conceptual interpretations. The explicit link between linguistic and conceptual structures is accomplished using REF. Having explicit knowledge about linguistic expression makes it easier to use the same knowledge for both analysis and generation and promotes the

interaction between abstract and more specialized linguistic knowledge. For example, the relationship between the indirect object and the conceptual *recipient* is a high-level REF association that may combine with particular knowledge about verbs of a more concrete nature.

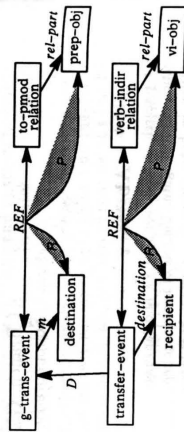


Figure 2: REF links linguistic and conceptual structures

Two important REF relationships in Ace are illustrated in Figure 2. The association of the *to-prod-recipient* at the level of *g-transf-ent* for "generalized transfers", a higher level than the *verb-indir-relation*, represents the knowledge that the object of the preposition "to" describes a more general role, *destination*, than the recipient described by the indirect object of a verb. Generalized transfer events include physical transfers as well, while in transfer events the recipient must abstractly receive the transferred object.

REF addresses the role relationship problem by providing a general means of associating linguistic and conceptual roles. Unlike systems such as Hirst's (Hirst, 1987), such relationships are often derivable from the knowledge structures in the network rather than being required explicitly for each word/sense template. For example, the relationship between the indirect object of the verb "sell" and the customer role is derived from the ROLE-PLAY between *indirect-object* and *recipient* and the fact that the customer plays a *recipient* role in the transfer of merchandise (cf. Jacobs, 1985). With the preposition "to", as in "sold the book to Fred", the role of *customer* is filled by virtue of its ROLE-PLAY relationship with the *destination* role.

C. The VIEW Association

The VIEW association is similar to REF, except that it represents metaphorical relationships rather than associations between linguistic and conceptual roles. For example, there is a broad class of English "transfer" expressions such as "give a kiss", "take a punch", and "get a back rub". The generalization here may be captured as a conceptual relationship, namely *being acted upon is often viewed as a transfer, in which the patient of the activity is viewed as the recipient*.

The example of "taking arguments" is similar, in that commands do not really "give" or "take" or "get" anything, but the language is extremely consistent in describing

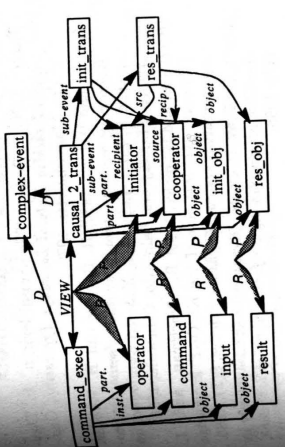


Figure 3: Capturing metaphorical generalizations

regarding them as if they did. Figure 3 shows a VIEW representing this relationship used to handle expressions like "getting arguments", "taking arguments", and "giving back a result". This representation has been slightly abbreviated due to its complexity; in reality the common manner of describing the complex *command-execution* event belongs to a broader class of metaphors along with "The frosting takes two cups of sugar". The VIEW as illustrated, however, encompasses quite a range of expressions. The power of this VIEW comes from the ROLE-PLAYs that capture the consistency of the metaphorical expressions, such as that relating *command* to *cooperator* and thereby to the *source* role of an initial transfer in an exchange (*causal.g.trans*). This VIEW thus provides a tool for handling numerous role relationships that otherwise would be enumerated as special cases in the system.

III The TRIUMP Analyzer

TRUMP (Transportable Understanding Mechanism Package) [Jacobs, 1986] is a natural language system designed for use in a variety of domains. The theoretical basis of the system is that the Ace knowledge base design makes it possible for a core of linguistic knowledge to be exploited across domains.

The algorithm that TRUMP uses to perform linguistic analysis consists of the following mechanisms: (1) A syntactic parser, which identifies linguistic constituents and instantiates linguistic relations that are tied to matched structures, (2) A mapping mechanism, which produces conceptual structures by following VIEW and REF links from these instantiated linguistic structures, and (3) A phase called *concretion* which finds the most specific frame suggested by other information and fills out the roles of that frame. For more details of this process, the reader is referred to [Jacobs, 1986].

Figure 4 is a sketch of the operation of the TRUMP

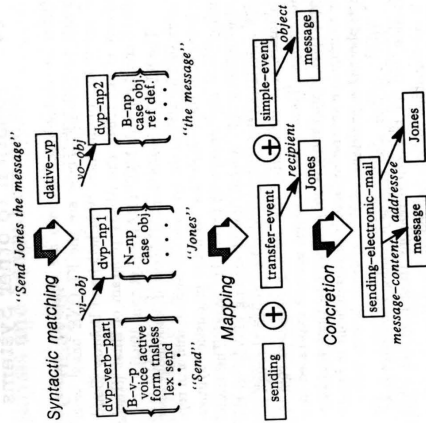


Figure 4: Operation of TRUMP

system, showing the results of the syntactic, mapping, and concretion processes. The application of role relationships is a major part of the work done by the semantic interpreter, or phases (2) and (3) above. When a linguistic structure is mapped, the interpreter must find the role in the resulting concept that appropriately corresponds to the linguistic role. Often this involves following a chain of ROLE-PLAY associations, and occasionally it does not completely specify the resulting role. For example, in "John gave Mary a kiss", versus "John gave Mary's cheek a kiss", the semantic interpreter correctly determines that the linguistic indirect object may express either the surface being kissed or the person being kissed. The semantic constraints on these roles favor the more likely interpretation.

TRUMP currently consists of about 5,000 lines of Common Lisp code, including the parser, semantic interpreter, knowledge base manipulation, and lexical acquisition mechanisms. The "core" Ace knowledge base consists of several hundred linguistic entries with about a thousand concepts, but this is not large enough to select a new domain without coding a fair amount of new knowledge. The system is currently being used, experimentally, in four drastically different natural language projects. While we are far from having a program that can easily function within a new application area, the exercise is proving useful in identifying natural language tools that do apply across domains.

IV. Relation to other Systems

Three knowledge-based systems are especially similar in design to TRUMP. These are the KL-ONE based work described by Sondheimer, Weischedel and Bobrow [Sondheimer *et al.*, 1984], the Absity program of Hirst [Hirst, 1987], and Lytinen's MOPTRANS [Lytinen, 1984].

The KL-ONE based work is closest in knowledge base design to TRUMP, as the systems use similar, uniform representational frameworks for both the linguistic "syntaxonomy" and the conceptual knowledge base. The translation rules of this system, corresponding closely to the REF associations of Ace, can also be applied through inheritance, thus facilitating the use of generalized role relationships. These rules, however, are not expressed in a declarative form; thus it is not as clear how they would apply to language generation, and it proves difficult to handle metaphorical expressions.

Hirst's system also applies a similar knowledge organization, but for theoretical reasons Hirst does not allow role relationships to be inherited in his system, requiring case-role specifications for each word sense. The "Polaroid words" in Hirst's system correspond closely to the concretization mechanism of TRUMP, in that roles are filled and more specific frames activated as more information propagates from the linguistic mechanism of the system.

Lytinen's MOPTRANS system is similar to TRUMP not only in the organization of knowledge structures (MOPs) but also in the choice of some of the higher level frames that are used to derive specialized interpretations via frame selection. MOPs, however, do not really support structured inheritance: although constraints and prototypes may be assigned at the concept/role level, a role or slot of a particular frame cannot derive from multiple roles. Thus, as in Absity, much of the knowledge used to handle role relationships must be handled at a very specific level. Also, this knowledge is attached to the individual MOPs, rather than being declaratively represented.

V. Summary and Conclusion

The ROLE RELATIONSHIP problem in semantic interpretation is the task of appropriately filling out the roles or slots of a candidate frame. Three knowledge structures of Ace—LINGUISTIC RELATIONS, REF ASSOCIATIONS, and VIEW ASSOCIATIONS—help to alleviate this problem by providing a hierarchy of linguistic structures and explicit role relationships that include metaphorical expressions. These structures are particularly useful in choosing among candidate concepts and in appropriately filling the roles of selected concepts. They combine with a representation such as KODIAK or KL-ONE to form an enriched framework for language processing. The TRUMP language analysis system supports the application of this core knowledge about language across domains.

References

- [Becker, 1975] J. Becker. The phrasal lexicon. In *Theoretical Issues in Natural Language Processing*, Cambridge, Massachusetts, 1975.
- [Bobrow and Webber, 1980] R. Bobrow and B. Webber. Knowledge representation for syntactic/semantic processing. In *Proceedings of the National Conference on Artificial Intelligence*, Palo Alto, California, 1980.
- [Brachman and Schmolze, 1985] R. Brachman and J. Schmolze. An overview of the KL-ONE knowledge representation system. *Cognitive Science*, 9(2), 1985.
- [Chafe, 1968] W. L. Chafe. Idiomaticity as an anomaly in the Chomskyan paradigm. *foundations of language*, 6(1), 1968.
- [Charniak *et al.*, 1983] E. Charniak, M. Gavin, and J. Hendler. *The FRAIL/NASL reference manual*. Technical Report CS-83-06, Brown University Department of Computer Science, 1983.
- [Hirst, 1987] G. Hirst. *Semantic Interpretation and the Resolution of Ambiguity*. Cambridge University Press, Cambridge, England, 1987.
- [Jacobs, 1985] P. Jacobs. *A Knowledge-Based Approach to Language Production*. PhD thesis, University of California, Berkeley, 1985.
- [Jacobs, 1986] P. Jacobs. Language analysis in not-so-limited domains. In *Proceedings of the Fall Joint Computer Conference*, Dallas, Texas, 1986.
- [Jacobs and Rau, 1985] P. Jacobs and L. Rau. Ace: associating language with meaning. In T. O'Shea, editor, *Advances in Artificial Intelligence*, North Holland, Amsterdam, 1985.
- [Lytinen, 1984] S. Lytinen. *The Organization of Knowledge in a Multi-lingual, Integrated Parser*. PhD thesis, Yale University, 1984.
- [Sondheimer and Nebel, 1986] N. Sondheimer and B. Nebel. A logical form and knowledge-base design for natural language generation. In *Proceedings of the Fifth National Conference on Artificial Intelligence*, Philadelphia, 1986.
- [Sondheimer *et al.*, 1984] N. Sondheimer, R. Weischedel, and R. Bobrow. Semantic interpretation using KL-ONE. In *Proceedings of the Tenth International Conference on Computational Linguistics*, Palo Alto, 1984.
- [Wilensky, 1986] R. Wilensky. Knowledge representation - a critique and a proposal. In J. Kolodner and C. Riesbeck, editors, *Experience, Memory, and Reasoning*, Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1986.
- [Wilks, 1978] Y. Wilks. Making preferences more active. *Artificial Intelligence*, 11, 1978.