PREFACE TO THE SECOND EDITION

in the years since the first editiOn. of this book appeared, Artificial Intaigence (Al) has. grown from scale laboratory science into a technological and industrial success. We now possess an arsenal of techniques. for creating computer programs that control manufacturing processes, diagnokse computer faults andi human diseases, design computers, do insurance underwriting, play grandmaster-level chess" and so on.. Ba_cie research in Al has expanded enormously during this period. For the student+ extracting theoretical and practical knowledge from such a large body of scientific knowledge is a daunting task. The goal of the 'first edition of this book was to provide a readable introduction to the problems and techniques of Al. In this edition. we have tried to achieve the same goal *for* the expanded field that Al ha,...; beccirne. ln particular. we have tried to present both the...theoretical foundations of Al and an indication of the ways that curreni techniques can be mod in application programs,

As a result of this effort. the book has grown. .11 is probably no lonQc.b.r possible to cover everything. in a rigle senile-ger. Because of this, we have structured the Mink so that an instructor can choose from a variety of paths through the chapters_ The hook ire divided into threc parts:

Part1. Problems and Search..
Part11 Knositillcidge R ilres-untation_
Part 111. Advanced Topics,

Part I introduces Al by examining. the mature of the difficLili problems that Al seeks to solver lt then develupK u] thcory and practice 4)1-heuristic search, pruvi ring o.ailed 4Allgorithrns lltr standard search methods,. including best-first search, hill climbing, simulated an imam s-ends analysis, and constraint satisfaction.

The last thirty years of .A1 have dernonstratod that intelligence requires more than the abiliiy to reason. also requires *giro* deal of knowledge about the world. So Part 11 explores a variety of methods for encoding knowledge in computer systems.. These methods include predicate logic. production nil es, semantic networks, frames, and scripts_ There are also chapter or both symbolic and numeric Ktehniques for re4isconing uncertainty. In addition', wc present some very specific frameworks in which. particular commitmons to a set of representational primitives are made_

Parts I. and rl should be covered in any basic course in AL They provide the foundation for the advanced topics and applications shat are presented in Part HI, While the chapters in Parts I and El shoutd be covered in order since they build on each other, the chapters in Part III fur the most independ.era and can be covered in almost any combination, depencling on the goals of a particular course. The topics that are covered include: garlic playing, planning, understanding. natural language processing (which. depends on dic undemanding chapter). par-4l11cl and. distributed. AI (which clopends on planning and natural language), Teaming, connectionist models, common sense+ expert systems,, and perception and 4.-Lction.

To use this book effectively, students should have some background in both computer science and mathematics, As computa hackground. th'y should have oxpericnce programming and they should feel comfortable with the material in an undergraduate data structures course. They should he familiar with the use of recursion as a program control structure. And they should be able to do simple analyses of the time complexity of algorithms. As mathematical background, t u de in is. should have the equivalent of an undergraduate colme in logic, inclidding predicate logic with quantifiers. and the basic motion of a deei2i.itan proCedure.

This book contains. spread throughout it, many references to the AI research literature, These references are important for two reagons, First. they make i Rpos.sihle for the AtUdent {) pursue in icipics in greater depth than is possible within the space restrictins. of this hook. This is the common reason for including references in a survey text, The second reason alai th s refercnces have bccn included is more specific to the content. of this book_ Al k a relatively new discipline.. In rrkany as of the field there is still pot complete agreement on how things should be done. The references to the sourrx literature guan.intee that students have access. noi just k one approach, hut to as many as possible of those whosc eventual success rii1 neied!i to be deemined by further research, 13oih. theoretical and empirical.

Since the ultimate goal of Al is the construction of programs that solve hard problems, no study of Al i$ complete without erne experince writing. programs_ Mc.iist Al programs are written in LISP, PROLOG., or sorripo specialized Al shell.. Recently though, a Al hit spread out into the mainstream computing world, Al programs are being wriiten in a wide variety of programming languages.. The algorith.ms pcesented in this book are described in sufficient detail io enable studenis to exploit ihern. in their programs, hui they are not expressed in code_ This book should probably be supplemented with a good book on whatever language i$ being used for programming in the course,

'hid book would not have happoned without the help of many people, The cotwirct **of the rriAnuscript has been greatly improved by the comments of Srinivas Akella, Ji ii Blevins, Clay Bridges, R. Martin Chavez, Alan Cline, Adam Farquar. Anwar Ghutoum, Yolanda R. V. Guha, Lacy Hidden, A] ay Jain, Craig Knoblock. Join Laird, Cliffored Mercer, Michael Newton.. Charle,s Peirie, Robert Rich, Sieve Shafer., Reid Simmons, He Simon. Munindar Tarnba, David Touretzk_ys Mazucla Vcioso. David. Wrobiewski, and Marco**

Special thanks io Yolando. Gil and Alan Cline for help above ii.nd beyond. Yolanda kept the project going under dcsperair d myrnstances,, and Akin spent innumerable hours designing the cover and bringing it i filo the world. We hank them for these. things and much, much more,

Linda Mitchell helped us put together many draft editions along the way. Some of those drafts were used in actual courses, where stufJenis found innumerable b.tip; for us, We would like to thank i hem as well as. their instructors... Torn Mitchell and lean Scholti. 'Thanks also to Speray for his help in producing the cover.

David Shapiro 4rind ate' Murphy deserve credit for superb editing, and for keeping us on schedule.

We would also like to thank Nicole Vcccbi for her wisdom and patience in the wor14 of high rusgiution printing. Thanks to David Long and Lily Mumrnert for pointing us to the right fonts.

Thanks 10 the following reviewers for their comments: Tigal Areas. University of Southern California; Jai trio Carbonell, Carncgie Mellon University: Dyer. 1._Tniversity of Wisconsin, Madition; George Erns!. Case. Wintern RestIrlit: University: Pat Lingloy, University of California. Irvine.; Brian Schmid, University of Michigan: and James Slagle, University of Minnesota.

Carnegie Mellen University and MCC provided us the environment in which we could write and produce this book. We would like to thank our wile-amts.. particularly Jim Barnett and Masan]. Mirka, for putting up with us while in wore %Tiling this hook instead of doing the tither thing,: we were supposed to be doing.

Elaine Rich
gala *Knight*

PART I

PROBLEMS AND SEARCH

CHAPTER

1

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WHAT IS ARTIFICIAL INTELLIGENCE?

der are three iirinds of i;JuiTurence: one kind whierstands things for itself, the other appreciata *what others can understand, the third understands neither for itself nor tii* rovri *others, is* first kind kg *excellent the second good and the third kind usdess.*

—Niccolo Machiavelli
(1469-1527i, Italian diplomat, politica]. philosopher,
musician, poet and playwright

What exactly i aftifir.:ial imelligence Although most atizmpts to define complex and widely used terms precisely are exercises in futility, it is useful to draw at least an approximate boundary around ihe concept to provide a perspective on the discus,sion that follows. To do this. we propusc the following by no mans universally accepied definition.. *Aritficiat* tirirelligenve (Al) is the study of how to make computers do thi.ngs which, at the morn tit. pcopte di better. This definition is, of course. somewhat ephemeral because of its reference to the current state of computer science, And it fails to include some 3rea_s of 1)0h:116 011y very large impact namely problems that cannot now I solved well by *eitha* cumputc.ips or people. But it provides a good outline of *hat constittilvi 4rlifici:11 intelligeoue, and it avoids the philosophical 'SATS that dominate attempts to dellae the meaning of either *firth:Alai* or hgelliporre, Intelestingly, though, it suggcsts a similarity with philosophy at the same time it is avoiding it_ Philosophy has always been the stony of those branches of knowledge that were so Orly understood that they had not yell become separate diseipline.s in their own right, As fields such as malhematics or physics beczine snore advanced, they broke off from philosophy. Perhaps ifAI SIUCCeedS it cars reduce itself to the empty set,. As on due this has not happened,. There are signs which scum to t;aggc,..t that the newer offshoois of Al together with their real world applications are gradually overshadowing it. As Al migrates to the real world we do not seem to be satisfied. with aunt a crInriputer playing a chess game. Instead we wish a robot would it opposiie to us al: an opponent, vistia]ize the real &Lard and. make the right moves iu this physical world, Rail maims 9Lcin lc) pasts the definitions or Al to a greater extent, A *Vie* read on. them will be always that lurking feeling that the definitions propounded so far are not adequntc. Only what we finally achieve in the future will help us propound an apt rielinition for Al! The feeling of intelligence is a mirage, if you achieve it, it ceases to make you. feel so. As somebody hag aptly put is – AT is *Artificial* inirelligencre till it is achieved: lifter which the acronym reduces to *Aiready Implemented.*

One must also appreciate the fact that comprehending the concept of Al at aide 1113 in understanding how uatural intelligrnce works. Though :i complete comprehension of its working may remain a mirage, the very *attempt* will definitely assist in unfolding mysteries one by one,

1.1 THE Al PROBLEMS

Whai then are wine of [he problems coniained within Al? Much ur the early ii.k.ork in the field focused on. formal tasks, such us. game playing and theorem proving.. Samuel 'nn a checkeN-playing program that not only played games with opponents but also used its experience at those games to improve its later performance, Chess also received a good deal of intention. The Logic 'Theorist wios an early attempt io prove mathematical theorems. It was able io prove several theorems (rpm the first chapter of Whitehead and Russell's *Prineipia* Mathemaiiica. Gelernier's theorem prover explored another area of mathematics; geometry. Garne playing and 111COre in pawing 7.i.harci the prop:sty that pimple who do them well are. considered to be displaying iricelligence. Dc-spitc this. it appeared initially that computers could perform well at those tasks simply by being fast at exploring a large n Li rnber of solution paths and then se leczing the best one. lt was thought that this proms required very little knowled.gr and could therefor be I:loyal¯rimed czsily.. As we will see Later, this as.sumption turntd out tEl he false sine c no computer k fast enough to overcome the combinatorial explosion generab..4.1 by most prublems.

Another early foray into Al focused on the sort of problem solving that we do every day when we decide how to get io work. in the morning, ofwn called ornminimsense reasorthig_ 11 hie luelm reasoning about physical objects and their relationships to each other (e.g.., an object can be in only one place at a time), As well as reasoning about actions and their et¯prisequences; ife,g.. if you let go of some it will fall to the floor and rank break)_ To investigate this. sort of reasoning. N'well, Shaw., an.d. Simon. built the Gnneral Problem Solver (GB), which they applied to several comnrIonsenso tasks as %Tic!! ias to the problem of performing symbolic manipulations or logical expressions. Again, no anempt was made to create a program with a large amount of knowledge about a particular probTem domain. Only 5 imp]e tasks were selected.

As Al research prugressoci and techniquo!..; for handling larger amounts of world knowledge wen developed, some plirjgre.SS WiLli Ina& on the tusks just desc...ribcd and new tasks could masonably be attcrriptcd_ Thaic include perception (vision and speech), natural language understanding, and problem solving in specialized domains such as medical diagnosis. and chemical analysis.

F'erception or the world around us is crucial to our survival_ Animals with much 'less intelligence than pcoplc are capable of inure S.Eilph IliiietrtM VISUiii ['exception than affi.! currrnt machines. Perceptual 417.40 am difficult because they involve analog (rather than digital) signals; the signals are typically very noisy and LISUa Ily a *Large* number of things (some of which may be partially obscuring others) must be perceived at once. The problems of perception are disamied in greater ideiail in Chapier 21,

The abiiity lo wee language to comIm KO calkr u was ac Ni gritty g.if ideas is paliaps the inosi important thing that separates humans from the other an The problem of understanding spoken language is a perceptual problem and is hard to solve for the reasons just discus!..;ed. But suppose we simplify the problem by restricting it to written language. This problem, usually referttd to as ntautai *language understanding, ig* still extremely difficult. ln irder to understand seniences about a topic, it is necessary to know not only *a* lot abotit the language itself (its vocabulary and grammar) but also a good deal ...,thout the topic so that unstated as sump! ions can be recognized. We discuss this problem again latcr in this chapter and then in IITIOrC. detail in Chapter 15.

In addition to these mundane tasks, many people can also perform one or maybe more specialized tasks in which carefully acquired expertise is uctss.ary Examples of .s:Bch taste include engineerifig design, scientific discovery. medical diagnosis:, and financial planning. Progriuns that can solve problems. in these domains also fall under the aegis of artificial intelligence. Figure 1.1 lists some of the tasks that are the targeLL of work in AL

What is Artificial intelligence?

A person li•ho knows how to perform tasks from several of rhL ca.teguries shown 3ri. the tig,.ure Innis the necessary skills in a standard order. First, perceptual, linguistic, and curnmonsensu skills are learned_ Later (and of COU Me for some people, never) expert skills such as engineering. medicine. or finance are :icquired._ It might. seem to make sense then that the earlier skills are easier and thus more amenable to computerized duplication than arc the later. more specialized ones_ For this reason. much of the initial Al work was concentrated in those early arta& But it turns out that this naive J.lissmirtiptioTi is riot right. Although expert skills require knowledge that many of us do not have. they often require much *lesg.* knowledge than do the more mundane skills and that knowledge is usually easier to represent and deal with inside programs..

Mundane Tasks

- **PerceptlrIn**
  - s irrn
  - **Speech**
- **Natural language**
  - **Understanding**
  - **Generation**
  - **Translation**
- **Ciwrirnonsenw. roasiirrinE,.**
- a **Robot control**

Formai! TaNks

- **Games**
  - **- Che.,5!-;**
  - **nackgran** rrycn
  - **Checkers -Go**
- **Mathematics**
  - **- Gen metry**
  - **- Logic**
  - **Integral calculus**
  - **Proving properties of programs**

Expert TitsEliginceri.ng

- **Design**
- **- Fault finding**
- **Manufacturing planninp**
- **Scientific analr:is**
- **Medical diagnosis**
- **Financial analysis**

Fig. 1,1 Same *the Task Dongairns of Artificial Intellipence*

As a result. the problem are where Al is now flourishing most as a practical discipline (as· opposed to a purely research one) are primarily the domains that require only speciali˜r.cd expertise without the vomistance of commonsense knowledge. There are now thousands of programs called *experi* sylirems in day-to-day operaiion throughoo all areas Or industry and gtivemment_ Each of these systems attempis purl, or potiaps all, of a practical, si if i t problem that previously required &came human expertise, in Chapter 20 we examine several of these systems and explore techniques for constructing theina_

Before embarkin on a study of specific Al problems and solution techniques, it is important a lmst to discuss. if not to answer. the following four questions:

1. What are our underlying assumptions about intellig,ence?
1 What kinds of techniques will be useful for solving Al problenTi7
3_ At what level of detail, if at all, are w trying, to moiclel human intelligence
4. How will w know when we have succeeded in building an intelligent program?

The next four tions of this chapter address the questions, Following that is a litriircy or some Al hooks that may l of inrue-rtst and a summary of the chaptE.r.

1.2 THE UNDERLYING ASSUMPTION

At the heart of research in artificial. intelli.gcnce lics what N owoll and Simon I I 9761 call the *physical symbol .rysfern hyparhesis.* They define a. physical symbol system as follows:

> A physical symbol system consists of a set or emit ics, callced -symbols. which are physical pal terns that can occur as components o 1 another type of entity c40 ley..1 au expression (or syrithol strucuire). TitioLi. 41 cymbal strutturt is composed of a number of instances. (or tokens} of s>inItids. related in sonic physical way (such as one token being next to another). At any instant of time the systcm will contain .a collection cif thcze symbol structures. Besides these wructures.. the 5y:id:al also contains a-collection Of prcv.:.cmcs that rageon cAprcssions to produce other mprmsions;
> x; sex of creaiioni. roodificAliort, reprmiumiari arK1 cicsimciirin. A physical gyntliol synern is a machine that pri.-Ndlticesi through film lial evolving. crEllecti on at-swill-Jul situ:110ov, Shah 111 Aystet PI e K I 'fiis in 't wollid (If ithiects wig than just these sjenall'ollic expressions theriselves_

11312)- then st;.ite, the hypcithesis is

> The Phi livai Symboi Sy.treFir hryprairesit A phyRical synnboi ciysteiri hod; die neces.sxy and se [went means for general inielligeoz acticm.

This. hypothe si is only a hypothesis.. There appear'S tt I *noway* to pruve: far dispruive it on Ilitizicm I L. ru Lind.... So ii nnav,i be subjected to empirical vli.lidation. We may find that it is false. We may find. that ilie hulk 4.1in the evidence says that it is irue. But the only way to determine its truth is by ex..perimentation.

Computers provide die perfect medium for this experimentation since they can be programmed to simulate any physical symbol systlem we 1[U% -11-IiN ability of Computers io scrim as arbitrary symbol manipulators was noticed very early in the. history of computing. Lady Love *Lice* made the following observation about Babbage's prop oNed Analytical Engi 11 e in 1842,

> The opttraii ng rnwhianisrn CP.11 even b thuloorn into action irw,krPendenily of any Libjlect to oparate upon (although of course no result could then be developed). Again, k might act upon other things besides numbers, were objects found %gill= mutual fund-arm:mai relations could be clpri.tvgai by thaw {al the abstract scilznice of operations, and which should bc also sLksceptible of adaptations to dire maim. or art: operating notation and mechanism of thc engine.. Supposing. for instance, that ine fund:unarml relations cif pitched sounds in the science of harmony and or musical composition were sustartible of such ex.pression and .i.idapiations. the engine rni&ht compo-sc elaborate and &derail-1w: pig of wok of any de gret or complex it y or extenc. I Lovel owe, M-; I

As it has become increasingly easy to build computing machines, so it Irns become increasingly possible to cunduct empirical investigatiuns 424 the physical symbol system hypothesis.. in catch such investigation, 3 panicuIar task that might be regarded as rquiring intelligence is selecled. A prugrain to perform the tack is proposed and (hen tested. Althoqhvbt- liavc~ not beim completely successful at creating programs that perform all the selected tasks, most scientists believe that many of the problems that have been encountercd. ultimately prove to be surmountable by more sophisticated prognms tha0 we have yet produced,.

Evidence in supporz of the physical symbol. sysiem hypothesis has come not only from was such as game ptoyingr, where one might most expect to find it, but also iron] as such a visual perception, where it is more tempting to suspect 11ie influence of iubsyrribolii,:.. processes. 14ov:rover, subsyrnbolic models (for example, neural networks) are byginning to challenge symbolic OFICS at such low-level tasks. Such models Etre discussed in Chapter I S. Whethei certain sub-symbolic models conflict with the physical symbol system hypothesis is a topic still under debate (e.g.., Srnolensky1198)). And it k important to note that ew.n the succ.nss asubsymbolie systems is not necessarily evidence against the hypothesis_ Ii is afte n possible to accomplish. task in more chin one way..

One iroteresiin&' attempt to reduce a particularly human Wiivityi the understanding of jokes, to a process or symbol manipulation is provided in the book *Mathematics and Iirmor* [Naos, 19801. It is, of course, possible that the h.ypodicsis will turn out to be only par ti ally true. P'ertiap,s physical symbol systems will prove able to model some aspects or hu Marl intelligence and nut others, Only time and effort. will tell_

The importance of Om physic:al symbol syste [n hypothesis is twofold. It is a significant theory of the nature cif human inielligcnee and so i of great interest to psychologists. It also forms the basis of the belief that it is possible lo build programs that. can perform intelligent tats now performed by people. Our major concern here is with the latter of these implications. although. as we will soon see, the two issues are not unrelated,

13 WHAT IS AN Al TECHNIQUE?

Artificial intelligence problems span a my broad spectrum. They app qtr to have very little in common except that they ;re hard. Are there any technique!..; that are appropriate for Ihe elution Or a variety of these problems? The answer to this quastinn is ye:ss alert we. What, then, if anything, can we say about those iechrikities besides the fact that they manipulate symbols? How could we tell if those techniques migh tbe useful in solving other problems, perhaps on not. traditionally rcgarried as Al tasks? The rest of this book is an attempt to answer those questions in detail., But before we begin examining closely the individual techniques, it is enlightening to take a broad look at them to see what properties they ought to possess.

Orke or the few hard and fast results to come out of the first three decades of Al research is that *intelligence requires* knowledge_ To compensate for itc n rig nverpnwcring zuoict. indispensability. Iznowldgr..! ixiissessts some less di :Arable properties, inctu.din:

1 It is voluminous_
- It is hard to uhanicterize accurately.
- It is constantly changing_
- It differs from data by being organized in a way that correspond_s to the ways it be used_

So where dots this leave us in our attempt to define Ai techniques? We are (weed c..onelude that an Al technique is a method that ex 014.44 knowledgc that shouId bc. rcpreserned in such a way that;

41. The knowledge captures generalizations.. In other words, it is not necessary to represent separately cach individual situation. Instead, situations that share important properties are gimped together. 11 knowledge does not have this properyjnurdinmtc amounts. of memory and updating will be required. So we usually call something without this property `4d '+ rather than knowledge..
- It can be understood by people who MUSE provide it. Although for many programs, the balk of the data can he acquired automatically (for example, by taking readings from a variety of instrumer, is), in many Al domains, most of the knowledge a program has must ultimately be provided by people in terms they unrkrsta

- it can easily he modified to corro...1 enri·o.-..; and icp reficct the aml in (WI" 'N1 1d Vitriphi.
- Ir rani b4 in a r rent marty in· ii if it is ni·Ft compleie.
- It ran 1-le ii....;;24.1 to h.1...V morcoine ills co, n hulk hy hu.iping 311.11'14)W [lie rang.e possikilities iitat musi timially be considered..

Although AI hniques tnuht be designed in I.:civil-1r ith tilLse iinpithod by Al problems.. there is. some Licgrec ra i irrdepond.c.ncc hit Finnproblems and prohicm·:icilieing techniquoN. k. is pussibli: ti solve. Al prohle,:rns without using Al tuchnigiats (alltlicyugh._ Lis We sugge_sted aho\ th.f..5se. suilimuns lure not. la.ely to *be* guild :F. And it is pos.cilile apply· AI icciiniclileR it) of non Al prolAcn),. Ilikel) m be a good thing ID d M EE E1[ti)1)1n11.... CILit poss.c...s indny t51' dturop._:leriYiii.."... as di P AI In 'order it!' try i cliarncterite AI tatirdques. orLiNcrn-ilidtp:Eldcra <<WiLy rm.Essible. iuok very different pry blems. and a scrics appruachcs for solviutz cach X51 llieut_

1.3.1 Tic Tac Toe

It this section, pw..4.ent a ..Lierici of three pro:...yarns. try play tictacioe. The propLan; in ibis; weios ini:rease

- Their 4..·I.Einplexity
- Their use. t11 gorteralid·....iticliio
- the of their knowlecipu
- 111C ntijr1SiblillrY 4:Pr the it ·...ipprt.5iLch. Thus, they move toward beim1 reproq.imitiuns of what we call Al

r Progrant

Data Structures

Lioatd A nine-Q.10 tnent col· re preoe n t i ng the bil3ard.. v hore IN; elements cif the *ector* correspond 10 the board

1 2 3
4 5 6
7

cicment contains I Eit Nalue 0 if 'lc corrchpc.mdiET, k blank_ l if it L· tilkd with an X. or 2 if it is 11.1l Li with an O.

..1oveitiblle A large vector of l'...1..6163 elements {3^9), cach cif which nine--cle[uent 4:o[7terits ot' this; iiectof chosen specifically to idluv, 'the aip.11·31hrn ii.P to.ork_

The Algorithm

To make a timovc. t.141 thc: followirry.

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2. the N.NliiiiraglZ1.1 in ...;skip I IC into the vcctor storcki there.
3. jibe ....eol.Pr L.,....14..tclod in ...iterP 2 1·c.hpviellts thc way (Ile IA1111clipk the rirloeke tliat hi. is id be made. So sc....t riciarL1 0.11.1.;11 iL dm!

Conlin en ts-

This program is liele-Fy **efficient in terms of time. And.** in theory. it could play ari optimal game of tic-tom-toe. Rut it Eras disadvania.pts:

- li take...s ;ri.)t ot spat in stor12- the tobli.! thin specifies the corro...t move 14.1 makc from each board probition.
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tecimique embodied ill. (his progn.iitl riteci an) of our requiruttienth for a :12 uod Al Let `sNee it' wt. Ctirl eifi) tlutcr.

Progrant7;)

Data Structures

Hoard A Rim:Li:km:IA vize[or representing die board, a. EIL:seribix] for Provairi I.. [4w inNtLtihd. of 1,Aing the nu inheN IL I , or 2 in each elem.!: nt, we 2 findicalin.r blank), 3 iine,,Iii..mtiniz Xt. tir 5 0).

Turn Aniri[LiTer move or thE game. i alitaut [o h p]ayed; I irdirates arit: First me,,ne,

The Algorithm

Thu moil) algoriairri [a SOS Sitbpruccdirreq:

Make 2 Retuirri.Li 5 if lid: center of the hoard is blank. thal is;. l3oard[5] = othorv.Ise, Chic TOLIMk; ;thy blank noncorrwr square (2. 4. 6.. or 87.

Noss %imp) Rc1MIrL if player p can ni.11. ',yin [Sri Ii !Re). otiverob tufri ihe numl)er of 111e square tlial constitifies nime. Thi% runclion eni.iblc the proTrani i i7 ;1 rtirl io Hock the c3pronim['n l'I.Psswiir 1.1.1>eraleti b citeckirT.. tine zit a i i 1 IH. each of the rows. co.ltimase and diag,onals. Beciluse thlo wxy Ya.14.11:N are nuilitwred. it {:an tcht 311c2ntire row (column or diagonal) to Nee if it iN possihilc hy the yalucs. of its ,L;111021105 together. Lithe product is IS 1:3 3 2}.. !hell X cox win. Jr thk. produci is 50 (5 x 5 x 2). then 0 find ;,1 ii nin rwA, cielerrnine which elerneiro I)1..:11111,;. And rimirri 1 fit minitier of 111.;,0 squarc.

rvti.ike% 11 mow. in \L1u:1.m ff 111ki preiCedilliCᴱ Sea% 11 co: RA kr I ti.) 3 it Turn is tvr 5 IF Tom i even, incromimtii by one.

has. ctraileg3.. far eat :h move it maw havt,:. tc i niake. I I EiLike.... *[be* oe,.11d-riumb12-rei.1 mores if it is playinp X, Ow evr...0rminbered mi.' 'es if it ic [Ailying (..). The; strategy for tan is as fc

the algorithm

I 1 (upper left oorniNl_

1 urn-=2 If Board151 ■N (Jo(5),, else Lio(1).

Boarci[)] i4 Malik.. (01.9), else (r (31,

If 1-³0..,.s.w in I X) is nix 0. then (1c)(Tios2.,winl X J [i_₁₂ h lock oppone.nt's wit kb-121,c. Go(rwlake2).

Torn=.5 11Posswin(X) i5 no! L P tl ai ri Go'Posswini X I) ILL.., 12lte Poss.witil 00 is not O.. IhIIi (it3(Pos:sliviiiL0)) block wit], clam lic)ar(11:11 is blank_ then GLii70., else Gia(3).. [lien:- the prugrarn is trying to make a lurk.]

Turn=6	If Posswin(0) is not 0 then Go (I)osswin(0)), else if Posswin(X) is not 0, then Go(Posswin(X)), else Go(Make2).
Tuiv.=7	Pos;swin(X) is not 0 then Go(Posswin(X)). eke if Posswin(0) is not 0, then Cio(Posswin( )). else go anywhere that is blank.
Tum=8	If 1aosswin(0) k nut it then Go(1³osswin(0)). eke if Posswin(X) is riot 0, then o(PosswiniXA. else go anywhere that is blank,
Tiam=g	Same EIS Turn =7.

Comments

Tlii:s program is not quite as efficient in term, of time a the first one since it has to check several conditions before making each move. But it is a lot more efficient in terms of space, It is also a lot easier to understand the program's sirategy or to change the mategy if desired_ Hu: the toml straegy has still been figured out in advance by thiz programmer_ Any hugs in The pmgrammer's tictarztuc phiying 'Will S11(11W up in the puagrarnss play_ And we Mill cannol generalize any of the program's knowledge to a different domain, such sis three-di IL tic-tac-toe..

Program 2'

This program is idEmii,..4.11 ELI. Program 2 excer row one *=hinge in th reprusientation of the baud. We again represent the board a a 111[0-e]enleni vector, but this time we assign board positions to vector demonic. as follows:

	3	4
	5	9
6		
		2

Notice that this numbering of the board produces a magic square: all the rows, columns., and diagonals sum up to 15_ Thig means that we can simplify the proces or checking fora pcKsible win_ in addition to marking the hoard as moves sire made, we keep a limp for each player, of the squares in which he or she has played. To check fur a pcissi hie. win. ror ono player, we consider each pair of squares. owned by that player and compute the difference between 15 and the sum of the two squares. this difference is not positive or if it is gutter than 9, then original two squares were not collinear and o can be ignored. Otherwise., if the square representing the difference is blank, a move there will produce a win. Since no player can have more than to squares at a :ime, there will be many fewer squares examined using this scheme than there were using the more straightforward approach o f Program 2. This show,.; bow the cboice of representation can have a 1119.i0f impact on the efficiency of a problem-solving program,

Comments

This comparison raisec an iniereRiing question about the relationship between the way people solve problems and the way cornpuiers do. Why do people rind !lie raw-scan approach easier while the nurriber-couriting approauh is rflorE..2 efficient for a computer? We do ran know 'enough about how people work to answer that qu.estion completely. One part of the aris.wer is that people air parallel processors and ean took at several parts of the and at once, whereas the conventional complier must look at the squares one at a time. Sometimes an investi alit r o In how people suave. prublerns sheds grcat light on how compuctrs should do so, At other times, the differences in the hardware of the two seem so great that different strategies seem best. As wc learn more alvtit problem solving both by people and by machines+ we may know better whether the same representations and algorithrm are best for both people and rrlachinv.s. We wili discuss this question further in Section 1.4.

Program. 3

Data SInktures

***Board* Po Ni tion** A structure containing a nine-element vector repres.eni ing the board, a list of board positions thaE could result from the next move, and a number representing an esiima.te of how likely the board position is to lead to an ultimate win for the player to move..

The Algorithm

decide on the next move, took ahead at the board positions that result from each possible move.. Decide which position i best (as described below), make the move that leads to that position, and aSSign the rating of that best move to the current position_

To decide which of a set of board positions is best,'do the following for each of thcm.

I . See if it is a win. If so, call it the hest by giving it the highe-y4 possible rating_

2, Otherwise, consider all the moves the .pp unerrt could mike next. See %Which of them i; worst for is (by recursively calling this prizotd.ure.).. Assume Cllr opixoricrit will make that. move. Whatever rating that move has, assign it to the node we are considering.

3, The best node is then the one with the high.eq rating..

This algorithm will look ahead at various sequences of moves in order to find a sequence that leads to a win. It attempt.% to rnaximite the likelihuod I winning, while ziNsuming that the opponent will try to minirnize that likelihood_ This kagorithm is canal ilk minimax prrrcedfire. and it is; dip-41152;W in &Lila in Cluiptcr 12_

Coritments

thlis program will require much more time than. either of the others since it must search 13 tree representing all possible move sequences before ma: mg etch move.. But it is superior to the other programs in one very big way: It could be extended to handle games more complicated than tic-utc-ioe, for which the exhaustive enumeration approach or Ow other programs would completely fat 1 apart.. It i;:in also he augmented by a variety of specific kind_c. of knoticiedge about garmF and how to play them.. For example, instead of considering all possible next moves, it might consider only a subset of them that are determined., by some simple algorithm, to be reasonable. And., instead of following each series cif moves until ere player wins, it L.outd seariA for a limited time and evaluate the merit of each resulting board position using some static function,

Program 3 is an example of the use. of an Al technique, For very small prrohlons. i i is Ic ufficiont. th.:in variCty of mar° dircct. methods. However, it sari be tr,s.ed in situations what tholie methods would. rail.

13.2 Question Answering

In this section we look at a series of programs that read in English text and then answer questions., also stated in English, about that text. This task differs from the lust one in that it is more difficult now to 2.3.21.e formally and precisely what our problem is And what constitutes correct solutions to it For example,. suppose that the input text were just the single sentence

Russia InaAsed mops on lho Czech 1-A-4-der.

[hen cither cu the following question-answering dialogues might occur (and in fact did occur with the POLIT1CS program [Carbonell, 19801j:

Dialogue I

: did R.w.,siiL kin tilik?

A; Russia the amt. iI could %kJ.: conirol ilf Czechoslovakia by scnclinv truitaps.

V'..hat sha uld. the lirlitu-d.

A: The 1,,..ni1cm,1 Stati;.:, should inien.ene

Dialogue

Q: Why did Rusia do this?

A; Bcvaw,L: a wanic.d to incrce its ipiluenci: over CzechoFil.o·...u.kia.

Q: What should rhe Starm tluir!

A The r1 i1 tbJ Smes should (leninmce the. fitis',ian action in the United Nations.

lin lit; POLITICS program,. {arts t; L:ori:Liti·tictcd by considering both iniput text arid a 2,0parall.12 mocicl of the beliefs and actions of various political entities. including Rli]SS:Ia, Whin th mode] is changed. as it was between I hese two dial ogu system% answers also ch[i·t * ,lit this example.. the first 4li aloi,Fue produced whin PMATICS a wade! that was. imorkled to corrospond 1.o !he helicfs or a iypical Arrierit·ari coriser...alive (circit 1917). The.• iecon.d dialogue occurced when POILCTICS tivu G 4 erk a model that wa.y iniellkkd to corcspcind to the beTicifs of a 11).02;11 American liberal Rif the same· vii.thigc).

T]ir4Fia L:ri I point her is. that cktining whai i r if) pr odtwo CE)Fterr sv..r.n· ti l• a quesiion may ix very hard_ quintion-answering Li-rota:Ens. donne what it [T]Ctirl!-; [t' be an ativiver by the procedure that is used to 4:olnpu1c [he. ;ins...loci·. TI on [heir lillihOIN In pecple Ica aLirce tli<<t [IIL anyivers Enrand by ithL: prograin ·111;11: 4)Lo modd 0. defined This comploiLlv saiihVactory.. but no bintur 4.11 cid·wing the problem ha2, yot bon found, For lack of a Niter we will do the male heck:. and illustrate three definitions of question answerina; each with cc)rresponding program drat imple.mcnti

order to he able compare the three programs, we il[tEs[raie all of them using thv roliowing

Miry V:dI111)pring for a new coat_ S 1112 1·4 mirl.Li a (J is r 4rc:uIiy Ntic poi it Nth rc. slie ilr.rovcreai that rfr•l reel ly with her fa'nritedres..,

We will also ;Attc...mpt onswer cach of the following, qui..!stions %filth each pro2n.un:

Qh What did Man· go !.11·topping ror?

Q2: 'Whir Mar?: find that

Q3: Di4.1 Mary billy anphin2?

Program i

This program iliternpts V answer question.; usiog the literal input text_ It simply maw bus to.xt this men 1_s i n ihe questifins against the inpot text.

D151 *to* Structures

ues[ionPutiorns A set of t•rnplsies thus match ccwrimon gucs.rion forms and proilikre t tic nt to twzd match 4.1.gDirist inputs, Templates. and patterns (which vi.ri cal] lest pallerizsi arc that if a template- matches s.k.Jucesst111.14 ail input quem.i[5n then its ii.y.ii:peilitc(1 tee paiterrio uwed to try to lin J appropriate 4.1wiv:cis i ii the For example., if the template "Wlirp did ,r y" in.atc127, .031 input question, ttic.r: (hie text pattern "x y matched against OK' imput temt !lie value az, is given al.. the amower to thc. toesricui.

MX(The input ·...timed simply as a itlog cliaracter string..
QUesticilr JIl ctu'r•in yucstion stored u a character string..

The Algorithm

To ansiiver a question., du ihe

I _ Compare each el Line 4.1t Quostimirriicrro;np..Diml tht~ it t i ;Indtiso thom: that ma11:11 to genierato a Ott of iext patierrri.
each of paiienis through a substicution that 12..eilerdles. alternative form, of oro for example.. go" in i on vinigln rmini.ti Acorn' in the 1r'.x Tilis.step gc,,. ne es a new, ex panda! set of text patrerns.
Apply each of these text pill:n 1s to Text., and calla:ft all din recalling answers.
4. Reply with the s121 cif unmwer..... just

Examples

Ql: The ierriplato "What slid .1: I' rr<a1 c-hes this -and..'01 1.erates the- text paticril "Mari *go shopping* for :." Afiqr thc poth.:..ni-stillsiitutifiri step, ibis pattern is. ex.paw.led to a soli of patterns inclu.ding hirkppinu for Z. and "Mary trmit slopriug. for .7. tatter pullers]. matOe..... [Etc i 11274.U.: the program, using a convention 'hat variables rnatch the longest poy.,sibl c string up to a!...endenee !.;.tich as a period),, assigns z ihc ....Atte, 'Ea new coat.' which is as the ansvccr.

Q2: Lillie!.6 [] Ie to %Try larve. allowing for the in of the ohji.21:1 of 'land bc.i.v.,eeil li'w 11)(0 [ry in, plum Nile 1 ikcid. the. i rr ram or the word "really in Llic. if. lind I he illrti L.)I.'nkie" for this que!...tim i hut iniswerablc. Trait or Eizeoullted fu

Q3: the quemiinn cari. hie answered, then reTonse is 'La rod ont_" Since no answer to this question. unlitained in tho lext, 2TISWer Wilr *be found.*

Commenes

'Ilk approach is clearly inadquu.te to answe.r the kirids of questions rpeoplc could ....LIn[•r reading i simplc teL E\ t_11 its 4.1.LISIA'er the 1·111:FM qUICSIIIOnS i delicately dependent Ofi the exact forth. v. Ilia qucsilicirrs arc stakal and on the variations thai .1A•iere in arsign 01 it e terririlatcs hind the pailern suhslitutirms tholi system tu:Lcs, rao, 111: slu:or inudeljulic.y til tbk program 10 peribrun ffic tea may m4.1kc you. vifon.Ocr how :such 4311 appro.;Nch coula cv.on b prop-NI:Ai. This prin.rraEri is sub.stantiall!... 11.traier :away from being useful 1.11.ait thu- program wt. looko,d n foi tic-tac-roe. Is this just a str.rivinzw. some other tr..4:11nicitio i 1:1111';good in 4.741i1 pari..1.41? wa5, yes. but it i 'orth ntolieming that tho 1[11S.pniErnram 1111.171Cly triatellhis palterns, percurniing .5011nlilh.31[Ons. and then answcrs using-s4raistzloro..ard. combiurmions of canned t.L,...xt serricriax fro&riricnLs !maw(' by matchE.1., i tilv same approach mat is used in o.n.o. 4 y r 'he mos.' famous Tirogaim..; ever written- ELIZA, wilLch wt' In 6.43. BiliL vi)i.k 'Dud. thc. rest of this sotiticrice uil prog.int..., it cheiold becorikb. dear that vi 11 we iiwon *c* he! tom "iirufkiiLl intL.....111.gcnce" dile% not indt34.1c i,Ls this except by u substantial Ntretclung

---

Program 2

This program first (..NArverts the irtpril (ex.' into a structurcd internal form that .1.tterirpis t Ii capwre the meaning of ihe scrii.cneelq. lt .1.1.sti. cum cos Liurstiooq intl.} that fon n_ Ir finds answer.; h TrratchinL2 structured forms agains! each other..

Data *Struchires*

EngLkihKum. A do ription of the words, grammar, and appropriate SC mantic interpretations of a large enough subset of English o account for the input texts that the system will see. This knowlmkge of Enslish is used bulbt to map input st.tritenoN in.co an inturnal, meaning-orien ted form and to map from such internal forms back into English. The former process is used when English ite.xt is being read; the taller is u_sed to generate English answers from the marl i n g urn o n m d form that constituaci the programn; knowledge base.

livid frem. The input text in. clura.cter form.

StructuredText A structured representation of the content of the input text. This structure attempts to capture the essential km11004u Enrontaiined in the texts independently of the exact way that the krurodalge was staid in English_ Some things that we.re not explicit in the English text, such as the referents of pronouns. have been made explicit in this form. Representing knowledge such as this is an impprtant issue in the design of almost all Al programs. Existing pro rams exp Col' E a Varieiy of frameworks for doing this, art alre three impartarit families of :iitech *knowledge repre_mitalion systems:* production rules (of the form "if .c then y")t giii.}1-and-filiet gtrticiarts. and statemcnts in matherratia Ingic_ We di u.s5 ail of these methods later in substantial detail, and we look at key questions that need t be answered in order to choose a method for a. panicalar program' i For now though, we just pick one arbitrarily. The one we've chosen is a slot-and-filler structure. For exampie,, the sentence "She found a red one she really liked," might be represented as shown in Fig. 1.2. Actually, this is a simplified description of the contents of the sentence. Notice that it is not vary explicit about temporal rulationnhips (for example, events are just marked as past *tense!) nor have we* nude any rte] attempt to represent the meaning of the qualifieT , "mally," It should, however, illusirate-ihe basic form that representations such as this take.. One of the key ideas in this stir of repre-scntation is that cm itirs in the represientaition derive their meaning from their con nevi ions 10 other cntitics. In the figure, only the entities defined by the sentence Jilt shown. But other entities. coat sponding to concept5 that the program knew about before it rend this sentence, also exist in the representation and can be re- ferret] to within these Inv stritetures.. Iii this example, for instarice, wi refer to the entities Mao; *Coai* (the general concept of a coat of which Thing' is a specific instance), Liking (thc Ecocral conccpt of liking). and *Finding* (the genera] concept of finding).

Event 2

iturialire :	Finding
rense:	*Pam*
agent ;	*Alm,.*
*objee1_*	T/ *ing I*

Thing I

ilisianc c.:	co *ltd*
color :	Red

Event.?

instance:	iiking
feinse :	Pare
modifie)7	*Maori*
object;	Thing .)

Fig. 12 A Structured *Represen* ration *of a Suntence*

inputQuestion The input (4wsdoc) in characier Crn_
SlroclQui.....:-.tion A structured represenution ithi; c..mtent of die qucsc.i4.1.n. 1114: structurc is the sizitnc.a !he one used l tt ropresoni the contoni of the input text.

The Algorithm

Curiveri n Lii inpuiTcxt into struciured kx-rii using the knowlizdg.e. cc.)ilaincti EngliNhKnow. 11`Litlirr.: COnSidCririg :Licvcrai different potential structures. for a variel.% (if ri...asons. includirig the. l'aer that Eng,iish wordi ctiri be arnhip.i.ous..English sinac[uri.n.; can be pruriourts IT have sevcr.al FICSSibie 2miecetionis. Then, to an....wer do. the follivo.i n12:

]. Cninveri the tities.ii.on sTRICLUTed form. again using thc knowleagc 01111'1;:liiI1Cd in Usc 5.1.)11112 SpeCia.] Marker ill the NittlitUrt iiridien.ii2 The. part of tit ari.F.:ture. that should to ucturrtod agih answer. This 1111ark.er will o tier!, correspond the OCCUITL'Ilee 1.11a question word like -who- Or "'Alai") in the The exud way in ...vhich this rnarl...i4 gel...-. done depends 4.in the form chosen for Peptesenting StrticilireciText. If IL qlrii Aral fil ler sin...14:11..1N, mtcli {LS 4 rmirlser GAF! be placed in one ot rn.i-Jrc slois. If a logical sl-..-.tcrn is tr..ii.7(1, Ii we vex, Markers will appear its ri tblcs i ii Lbw for rnulas repro semi
lielatch this structured form against Structuredrext.
Rt,.turri tlFre Rilskiver those pans. 4.4 ihe to 'Hui timich the sve.rileni oil

Examples

Q1: This question is answered stri.142htforw;mi1y with, J ricw
Q1: This. (}nc also is arrsv.cred sucecsisfully "u.rcd eclat".
Q3: This one.. thoat4li, c...innot be answeced.. since there is rio &wed remxirr.u.e to it

Comrnents

This approact, i uhsiantiolly more (know]edgc)-bos.ccl Own tlit ht firs! prognan and St) is more 42111-cuive. It can answnr most quI2stinns w. which replies are ountainctl. in the lext. and it is much le!is hrittle than the Tint program with respect to the *exacr* forn i 4.11 the texc iArld the questions. As w expect. based on our 'knee with the. rl ati e rr) recognition Rlid tic-tac-toe progirarris. the price we pay for this increased is time. Aleut seurchinv, variouslint 1 41 laso.-; EngliNliKnovy., StructurcirThitt)..

On word cir warning is approprixto hem_ Thu problimi 4.1rpoxlacing ;J knowledge basic for English that is pl.merful enough lief handle a wide ram N. FmElish inputs i cvery k discussed al gri2aler leng,r.h Cli aptc r 1 5. Iri is now recol2ilifoLl knowledve Eriulish aki]le is 1-14.11. ...Ric:Litt:etc ill VILeral enithiC ii pvoltrion to build ihe kind of slrocuired shown lioru_ Adt!itional world %via(which the text .d.cals i oncn to support lexi4.1 andsymartic d.isuorthiguatiort and Elie corroct tuisigrirnent t1 i aluccedeins Li.) pronouns. art' mg other things. For example. lit the text

Mary wail ol up To ihn: :%1.11L11T2r,imi Sl1c: asked where 'he ILTY.BIEMMI'1

it is no(possible to determine :..N.1-Lat thi: word -she- reinrs its without kno.o..ledge ;about the roles of Oustomers and. &Liles people in mores. To see this., voitirast 01.1-rIO:1 iiTiteCedent NhC that L•Xi kill the correct 1.11c,2..-eclelli k:' the first occurrence of "she" in ihe following.

hlary u[..to person, asked her if ...lit' iwedk..t.1 mil% help.

Iii the sin plt case illuqtated our CE }at-buyirt example. i L k pc.)!isi hie to derive correci answers. io our iirm. o questions without any knowled.2c about stores or CikatS., Una till: fact that sortie :such additional inibrniation may he neccs!..ar.... it!. Support qllnilit)31 answering. has ILInzady been illustrated by the lailLIre of this

prograin find. au ....)r)mvizr to quizsiion 3. Thus we see that airhough extrad.ing structured repriesemation or Clic meaning of ihr:: input text k au irnprovctnent over the meaning-II= lipprovuzlo of Program 1, it is by nu meang qufficient in general._ Si:' aced co look at an even mare sophislic-amdl *(i.e,,* know [cd ee-rich) approach! which i4wliai we do nexl-

Program id

This program converts the input text into *a* structured form Lh L coilnirri the meanings of ihe wnteng.Les in the tem, and then rt L:Or]lbitleR thaT form with other struo.tured forms [bar des42ribe prior k] at atyout the otijecEs. and situaiirms invc.ilyod in the to I I u.liswors Lluostions using this augnitiTted knowledge struclure,

Data Structures

Wored.biludcl **A structure.(1 representation of hwk.grotind world knowledge. This. structure contain% kiinewle44.e aboui objects. acliOns and siluatic.v... r..ha[are &scribed in the input text. This smiciu.n.: is used !{ conm.ruut. Intez,ratulTexit from the input to For example., Figure 1.3 shows an examplc of a iitructure hu.1 reivrewt)1...s. symertI li knowledge about shopping.**

Th **Li kind of stored k now Ii dgc shout stcruitypical exen1L9 is cal I.cd D, *script* and N discussed in mare dutail in St..citi on 10_2_ 'Ube nomiion used here differ from the one norm allv iised in !he 1i1r2raitire for of 111c prime nolalion describes ;in c.)bjed. of the surrie type as tlic unpr mcd syriiiNil that irnay or may riot refer to the identical object. in the case of oilr text for eximplc, M is a coat and M' is a red coat. Brunches in the Figure dcs.criht: attemu.rivc paths Ihniugh thL.**

1. G enters L

2. C beg nu looking Rround

3_ C locks for n specific M

1. C looks for any inieresiin.g M

5, C Euks {Or tFelp

S.

7. C firlds M'

8. C fails. tip find M

9. C leaves L

10. C buys kr

C leaves L

12. go.os6ep. 2

13. C leayes

14. CR!ke5Mfr Fig..

13 .1 *Shopping Script*

EieliShicnOW **StirT3C is in Fri Tr 2.**

Input' rex I **Tlre iliput text in charactier tors L**

Why couldn'i [1,1].dary's brother reach her?

with the reply

Bee:dust

But to do so requires knowing that one cannot be al two places at once and then using that fact to conclude that Mary could nol have been home because s.he was shopping instead. Thus, although we avoided the inference problem temporarily by building ImegratedText, Which had some obvious inferences built into it, we cannot avoid it forever, it is simply not practical to anticipate all legitimate inferences. In later chapters, we look at ways of providing a general inference mialhanism that could he uged to suppart a prugrarn such as tic last one in ibis series.

This limitation does not contradict the main poi nit of this example though. Ira tatty h. is additional. .11·iderIce for that point, namely, an effectiii..e question-answering procedure must be one based soundly on knowledge and the computational use of that 'knowledge, The purpose of Al· techniques is to support this effective use of know ledge..

With the advent of the Internet and the vast amount of knowledge in the ever increasing wchsites and associated pages, came the Web based Question Angwering Syqterns., Try for instance the START natural language question a.nswering. system (impisiart..csailsnit.edul). You wil! rind that both the questions – *Whim' is the ccipital 49f India?* and Pr *Delhi the capita/ of India?* yield the same arudwers. viz. *New Delhi is the cailital of India.* On the contrary the question *Are ihrre wolves in Korea?* yidds 1 *don't krieW* if *thew fire wolves in Korea_* which looks quite natural

1.3.3 Conclusion

We have just examined two series of programs lo solve two very different problems. In each series,. the final program exemplifies what we mean by an Al technique.. These two programs are slower to execute than the earlier ones in their respective series, but they illustrate. three important Al techniques:

- Search—PI-4w idvs a way of solving, problems for which no more direct approach is available as well as a framework. jut(' which any &r .o. tzchniqucs that au available. can be crnbedded...
- Use of [nowledge—Provides a way of solving comp]ex problems by exploiting the structures of the objects that are involved.
- AbgraCtitill—PMVidiCS a way fir separating important rcaturvi and variat inns from the many unirripoitimt ones that would otherwise overwhelm any process.

For the solluiun of hard problems, program that exploit these techniLities have several advantages over those that do not. They are much Yens fragi[e; they will not be thrown oil completely by a small perturbation in their input. People can easily understand what the prograrn's knowledge is. And these techniques can work for large problems where more direct methods break down.

We have still not given a precise definition of an Al technique. it is probably mit possible to do so. But we have given some examples of what one is mid what one k not. Throughout the rem of this book, we talk in gicat detail about what one is The definition should then become a bit clearer, or less necessary.

1.4 THE LEVEL OF THE MODEL

Before we ct out to do samethi rig, i t i, a good idea to decide exactly what we are trying to do. So we must ask cur Ives, "What is our goal in trying to produce programs that do the intelligent things that mock do?" Arc we prying to produce prograrm that do the tack (be same way pimple do? Or. are we attempting to produce ptvgrams that simply do *tho* tasks in whawver way appcars easiest? There have been Al projects motivated by each of the goals..

Efforts lo build prugrams that perform tasks the way peupk do roan be divided into two classes.. Programs in the first class attempt to solve problems thin do not really lit our definition of an Al tack They are prohlems that *a* computer could casily solve, although that ersy solution would exploit mechanisms that do not seem to be available to people. A classical example of this class of pr rim is the Elementary Perceiver and Memorizer (EPAM) [Feigenbaum, 1963], wh[ch rnemnrized associated pairs of nonsense syllabtes. Memorizing pairs of nOnsell se syllables is ewiy for a CuMpUter. Si reply irrpult them. Tu rctricve a resixyrisc syllabic given its a_ssoc iatcd stimulus one+ the computer just scans for *the* m.imulus. syllable 'Ind responds with the *nn* .1.1.0r011 Ilext tr.) it_ But this task is hard for people, EPA M simulated one way people might rerforro the task. It built a discrimination net through which it could rind loges of the yEy1.1 able_s it had seen_ It alb !trued, with each Wraith's image, a cue that it could later pass through the discrimination net to try to Ilnd the correct response image. But it stored as a cue only as much informaiion about the response syllable as was necessary lo avoid ambiguity at the time the association was siorcd. This. might be just the first letter, for example:. But, of course, as ihe discrimination net grew and more syllables were lidded, an ol.d.cue, might no longer be sufficiant to identify a response syllable uniquely. Thus EPAM, like people, sometimes "forgot" weviously learned responses. Many people regard programs in this rim class to be uninteresiing., .end to sorne exient they are probably right. These programs car', however, be usefUl troupl:s for psychologists who want to test theories of human performance..

The second class of programs that attempt to model human performance are those that do things that fall rnore clearly within ow- definition of Al tasks: they du things that are not trivial for the computer. There are several reaSOFIS one might likant to model human performance at these sorts of tasks:

1. To test psychological iheories of human performance, One example or a program that was written for this reason is PARRY iColby. I 9751, which exploiied a model of human paranoid behavior to 5imulliate the cotiversational behavior of a paranoid person. The model was. good enough that when several. psychologists were given the opportunity io converse with the prrograrn via a terminal, they diagnosed its behavior as paranoid.
2. TEl ena.blz ccirnputen to understand human reiasconi ng, For exiaropic, for a computer to be ahl e to read a newspaper story and then answer a question+ such as "Why did the terrorists kill the hostages?" its program must be able lo simulate *the* reasoning processes of I:pulp.
3. To enable people to undentand computer reasoning. In many circurnstances, people are reluctant to ray on the outpul or a computer unless they can undermand how the machine arrived at its n....-sallt. lithe computcr's rea_soning process is similar to that u1 people then prOduCing an acceptable explanation is much easier.
4. Tti exploit wItat knnuledge wc can glean feline people. Since people are ihe hosi-known periormen; of MOsr of the ta.sks with which we are dealing, it rim kes .a 1E)11 01 Sense IID 111o).. IL) them for *clues* as to how to proceed,

This. last motivation is probably the most perVasiiie of the four. it motivated severa1 very eady systems that attempted to prodUce inte]ligent be by, imitating people at the level of individual neurons . For examples of this. see thu c-arly illOrATtiCall WWI; of McCulloch and Pitts 119431, the work on perccptrons.., uriginidly developed by Frank Rosenblatt but best described in *.Perneptrools* [Minsky and Papert, 1969J and *Design for a Brain* [Ashby, 19521, It proved imposible,, however, io product even minimally inielligent behavior with such simple devices. One rea.son was that there were severe theoreiic al limitatiorn_s to the particular neural, net architecture that was being, used. More recenily. several new neural net architectures have been proposed.. Those structures are not subject to the Salle theoretical limitations as were perceptrons. These new architectures are loosely called *connectionist,* and they have been used as a basis for several learning and problem-solving prog.rains. We *hags' snort* tl II say ahout them in Charier I R. Also,. we must eonsi der that while hunum brains are highly parallel devices, most current omnputing systems are es..wntially serial engines.. A highly successful parallel technique rnay be computstion.ally intractable on a serial computer. But recently, ply because of the existence of the new family of parallel cognitive models, AS well as tecause of i he general prornim of paddle] computing, there is now sub·stantial i nterest in the design of massively pamllei rnachinv. to support Al programs..

Human cognitive theories have also influenced Al to look for higher-Level (Le, far above the neuron level) theories that do not requite massive parallelism for their implementation. An early example of this approacit elm be *seen* in GPS. which are discussed in more detail in Section 1(5.. This same approach can also be seen in much current work in natural language undermanding. Tlic fuilure of straightforward syntactic parsing tnechanisms to make much of a dent in the problem of interpreting English sentences has led many people who are interested in natural language understanding by machine to look serimtsiy for inspiration at what Dale we know about how pt,...ople intelvret language. Aid when pop* who are trying to build programs to an.;,alyzt pictures discover that a filter knciion they have developed is very similar to what we think people use, they take heart that perhaps they are in the right track,

A you can scc. this last motivation pe.rvados a great many ;gess 01AI-research. In fact, it., in conjunction.with the other motivations we mentioned., tends to make the distinction between the guat of simulating human performance and the goal of building an intelligent program any way we can seem much lesF. different than they *al* first appeared_ In either caso, v" hay wr rcilly need is II guod model of die processes involved in intelligent reasoning. The field of cowl,' *Uhl-* .1 IC kik T. in which psychologisb, linguists, and computer scientists all work together, has us its goal the discovery *of* such a model. For El good. sUPfirCy of the variety of approaches contained within the field, see Norman [198 I lb Anderson [1985], and Gardner [119851

1.5 CRITERIA FOR SUCCESS

One of the most irnponant questions to an_swer in any scientific or engineering research project is 'How will we know if we have succeededr Artificial intelligence is no exception.. How will we know if we have constructed a machine that is intelligent? That question i_s ai least as hard a...; tlic unatisivcrahle glicstiun "What i3 intelligUrleer Hilt can like du anything to meal.= our progivs_sli

In 1950, Alan Turing propased the following method for determining whether a rnael-nne can ithinic His m2thod has since become known as the *Turing Test.* To conduct this tees, we need two people and the machine to be evaluatcd. 002 perion plays the role 01 the interrogator, who is in a separate rixim from the computer and the other person. The interrogator can ask questions of either the person or the computer by typing questions and receiving typed. responses.. However, the interrogator know& them only as A and B and aims to detetrnine which is the person and which k the machine. The goal of the machine is to fool the interrogator into believing that it is the person, If the machine succeea at ibis, then we will coniClUde that [he nwhine.can think, 'rho machine is allowed to do whatever it can to fool the interrogator. So. for example. if asked the question "How much is 14324 times 73,98.1?" it could wait several mirrutm; mind LS= rrspond with the wtiorng answer Miring, I.%31.

The more serious issue, though, is tine amount of knowledge that a machine would need to pass the Turing tet. Turing gives the following example of the sort. of dialogue a machine would have to be capable of:

Interrogator:	In the first line cif your sonnet which reads "Shall I compare *thee to* a stirrhrric.eg days" would .not "a spring day' do as well or better?
A:	It wouldn't Kan.
loternagator:	How about "a winters day." That would scan all right.
A:	Y. but nobody wants to be {:ampareti to a wiriter's day.
Interrogator;	Would you say Mr. Pickwick reminded you of Cltristmas?
A;	In a way.

Ifideirc31la1oi1 Ytt winieriL4 day. and I do rivil ibink ?Or_ Picloivick would mind coiriparistiri.

A: I don't think you'tr serious_ L a 'Ivinter*s day or FOLIOS. EI typical wintcr's day, rather than :1 special one like Chrisin-as_

It will. Ih• j lon.e time beforic a computer pak.!,es. the Turing. SC,IIle p42.1.1p1E' I LL1 is vc none VVer will. BM WC arc Willing i• the for less than a complete imitation of a person.. Can wt I1.' ei-I klu::thc. achievement of Al in Hum! finmEtin.,5?

Often tho Linsi.s-or 14? Lehi s question is. yes_ Sorni2tirries i1 is possible to. get a fairlv precise measure ihe a pi-41gram. 'For ex ;ill pile. :1 pr-4.1griim can ackpiiiv Li che in the same as a human plo,)]..,r, 1104 rating. B. 1111:rating_5 pho...ers whorn -din:. program hem_ Alrvigh programs li.,0.12. at'Auired L he taiings hi.-1-102-L. than aic vast majority of human playon,, jro orti.e.r pr olhlou. dorriairr.,, a .11275¹.1/4 precise ineasu•c, of 3-4 progranl`-.a1 h ievemeut I possible._ Fror ;Ltri p I e. I)EN I)R A L is a program 1 bat organic compounds &termiric stn.' L IL I e_1 Ci hi I rd III. _21.'1 i.1 Pa Ti c irieiLsttre. 4.}i' AL's le% el of croirripired 1 hill-flail chemists, hut it liras pro4litcrEl LinHlyses tllra i lthvo ori.,12,inal reu11 Thu:, it is certainli2. pier-funning coirily.n.crill).

ill other le 1:1 inic.01 domains. it is possible to compare the time it takes for a program to cti fnpJC tc a tx.ii; to the Ii required h y Li per m.lr) ILI LIB the svirrie thing. For example, there arc v1_¹1 e rhil [mgrativ, in List by compmer courivinicis t rr 4,:orifi2Liri.. pal-OR:War ...o..slems 10 J reeds cot v.11114..11 the pioneer was a progrian called R11. 'Thor.: progriims typically ropin.- ininotes perform laNks that previously required how. 41t a skilled c.nr.inecr'N tinic._ Stich priPir.17.1111S art e....-alitoted by 'coking at ithi2 botiorn - wholicr tlicy s.ave {or makeJ money_

i• marry eiveryday t1101.1.h. it mai,r he. IlarLier Co uneasure a pri..wurri's .rfoirmiaili:e. Suppose, fr Wt. u"}(i program ter rrarap11ni.s2 slimy_ For pnthierns such as this, the ho dl. It is usually prod,:r-arri respoitcled hi a vi dy thai r...rson could !lave.

If cur program 1irk SI111L1[310 hu]num performance it a tusl.:;_ uL 11)•2 me.al..t.ire of t2:41ioni 10. which t.ho proFraria's hellaih-i i r ci iirespo rids to that pc rionii [ince_ nwasurcd h ...-a.rious kinds of experi •;111d pil.1100)1 ;1111i.11 y .IiILiiiswe (141 nc.11 d Ctrl }12 vim I that duos kiz., vhtli a i poNsible. We • aI1 I.1.1112 t hii L Caik when peoplc do. Nelarious. I. En. el arc] by psychologists. for cornpuriris. individual and for ic..stinl,r modol..s can EaLr lased to do this wialysis.

Wc. :Lre forcoil to 1:1,..5nclock that th4-... qui:...stion of 'Li:hotter a machine has intelligelicIZ or can think is too netwloto; to .Linswer preci..si:ly, BLit it is often pc);•!•;iblu: to construct a onropulor prugrairi that performance. st.i.iirdard. for panicular 'ask_ That ducs ri.ot incaii. dial the pr4i.g..ram don the task in tht best possible way. It iineans Pnly that 'owe andersiarid ail least Orlt ti' il:y LA doing at least pan of a task. When ci out to design an AI pro,gran], w should attempt to specify as vh-c11 possible the cri(eria for success Ilbr that particular program lunetioning in its restricted drionaitt For the Criorncri L that k the best 'eke can do,

14 SOME GENERAL REFERENCES

There are great many L,clorce., of information abolii imel]igence. scrme survey The broadest arc th.c inalii•vt)lonic Of *id... I* 9.1] En ; X *of* A rtiffrial Intelligence 11Sheipiro and Edo-41th. 0871. hPrIth Of which conitlin anicle.s rn each of the major iDpics in the field_ Four 4,3r,,hici- IN) 01;,,s 'h al providc gond .c)...cri.ievo, (A the- lield are *Artificial lateltigerret. riNinslun. 198-11, brimiluction 10 Aniirr&oi !wen..gowe* [Chttrilii.d]. and rsleDerinoti.. 1985.1. *Logicalf huroi4aridArrs.4.11 Artificial [Gene...on2th* ..inuf Nilsson. ii.M7], urN4.1 *The* h'Icniarsh. *rthreffigrnrelTuliimolo, L 1.*00C more re trio *EeI]* scopi2 i c Principfe", Eif_41.1i17.r '4'rNik . 9140t which comain_s a CorThal [tcairiberii of sonic gonicral-put] osc A1 hrii(tu

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Thr2 major journal of Al research is culled Nimply *inielli:;·ence.* To addition, *Cogairfre Sejetrue* dccorcd [0 paper:, deu.]ing the overlappinE. areas of psycholo.gy. arid art i intelligence. Ai Magtizine is a E1101·43 ephemeral,. IcAs technical rru.ig.w.cirbo that is published by the Anwrican Assoiziation for Artificial intelligence (A AAI). f.EPE *Erperi. 'PER* Tronliarrimrs. on *SIIWIrefriS, Man tilnel CyhrTiljfIre ,* /EFE Tarn enstrairmA *pri Neural .verwrirkv* sevcr;il oitier journal!, pilbli.,11 poiper.... a broad per [rurn or A application EL Perb;iiih.

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ln u.ddii.jun 10 iiiicse 2 eneru.I rcrerenon, them 12-74.isc!...rr wholc irray ni papers and hook·; dncribing individoal Al projbas. Rather than trying to lit them all hero, t1u arc refer·J·12d to op; 4pppopriale. Ifiri.K.igliouo the this. book.

1,7 ONE FINAL WORD AND BEYOND

What crodusiow; ean we draw from ibis hurried. introduciion to the major questions of AP 'Mc problems are. varied, in[cresiiimg. arid hard_ scl]ve them. w will have ti chi! programs anti P rhap almiter u 'tag of human thoulit. M1t1 .114.11 Elk; ihe best we inn lo iteria Lr amt e cwiri 1X11 ir wi havc soivcd the problems, wind then vie must try in (14.1 so.

1-1i·iw actually to *go* about golviny think: problem!, iN the topic tsar the rest or this hoc k. Virre need mizthods. to hdp LIN Mik Ar s serious dilemma:

J I Ain rrii3!;.t contain ;.I Lou of knowledge if it is to handle. anythirlp bull trivial *toy* prublornis. EhLt *al..* the' 4.im 0 u litol·k rto od":212. Lirows. it becomes. h.arder mss the u.ppropriate things when needed, so mc,reknotAilledge fl uNt EL LLIdo..1 io H ut now Ebert t even mart: knowledge tc a inanN.re, s() V1111112 itlUsl 110.;' Jitliled. and r forth_

Our in Al is 10 construe! working. proE,rrarns that solve the problems we are interested in.. Thruughout MOM tar !his. book. Wt` ftacus. tan [h• design of repro:.;eniatitHi rnechliniNms :Lrid algorithms that Carl USCCI by pl'OrFallik; WE solve the problem., We do not sivrid much time discth.sinE the provrarrrrning proc'iss ptquired E ti turn chew Eile6igns into working pfogranh. in theory, it does nE 5E]rrat *ter* how thih. process is carrioil oul ill what language it k Mont, or can What machine the product is run. In practice, of course. it i5 Oflett much eiNier paxioce as program uF.ing of ceJti rather than another. Specifiru.11y, Al prtrgrrnrI 1 apa easiest to build using larkpiap:s that Iu e been designed io uppert syrnb4.1tie ruttier th:.in prirnarik·... numeric computatiorn.

For a variety of reasons, LISP has hisiorically been the most commonly used language for Al programming. We say little explicitly about LISP in this book, although we occasionally rely on it as a notation.. There used io be several competing dialect of LISP. but Common Lisp is now accepied as a standard. 1 fyou are unfamiliar with USK consult any of the following cur s; LLYP1Winston and Horn, 1989]. *Common Lisp* [Hennessey, 1989.11. *Common LISPvraii* IWilensky., 19861. and *Common Lisp: A °elide introdliction to Symbolic Compiraation* rfourevlcy, 11989a I. For a complete description of Corm-ion Lisp. see alitinnat± *Lisp: The Reference* [Sleek. 1990]_

Another language that is often used for Al progranuning is PROLOG, which k described in *Chmptcr* 25 And increasingly, as AI makes its way into the conventional. programming world. Al systems *are* being written in *g* c-nend purpose programming languages such as C. One reason for this is that Al programs arc ceasing to be standalone systems; instead, they are becoming components of larger systems, which may include conventional programs and database-s of various forms. Real code (foes not form a big paxi. of ibis book precisely because it is possible to implement the iechniques we discuss in any of several languages and it is important not to confuse the ideas with their specific implementations. But you should *keep* in mind as you re-ad the rest of this hook that both dm knowled,gc structures and the problem-solving strategies we discuss must ultimately be coded arid integrate,d into a working program_ This process will definitely throw morre light into real world problems faced in the implementation of A] techniques.. It is for this reason we have imroduced Prolog to cnsure that you ink, not end up just reading and believing_

AI is still a young discipline possibly in the 5CUISC ii Et Nile has been achieved as compared to what was expected. However one must admit a I Lt more has been learnt about it_ We have learnt many things, some of which are presented in this book. Rut it is still hard to know exactly the perspective from which those things should be viewed. We cannot resisi quoting an observation made by Lady Lovelace more than MO years. ago:

In considering *any Rev;* subject, there is frequently a tendency, first. to *eiverrizie what we firvJ* to bc al wady interesting or tr markable; and, secondly, by a mill of natural reaction, iowiderrobte the true pitate or the case, when we do diwavcr That 1;:par maim.; have itivia_ssed thusc that wcrc rcailly teriabic. 'Lovelace, 1961 1

She was talking.about Babbage's Analytical Engine. But she could have been describing artificial intelligence.

While defining Al in terms of symbol processing it would only be right for us to inspect the problem of *Symbol Grcnindirit* {Stevan Hamad,, IWO. The Symbol Grounding Problem, Physics, D42. 335-3461 and not forget about it whilo grasping any claw concept_s. discussed in this book. Harmad defines the symbol grounding problem citing the example of the Chinese Room [Searle, 19801. The bask assumption of symbolic Al is that if a symbol System is able to exhihii behavioni which are indistinguishable from those made by a human being, then it has. a mind. Imagine such a systorn subjected to the Turing teal in Chinese. If the s.ystern can respond to all Chinese symbol siring inputs in just the manner as a native Chinese speaker, then it mem (seems) that the system is able to comprehend the meaning of the Chinese symbols just the way we all comprehend oar native languages. Searle argues that this cannot be and poses the question — If he (who knows none of Chinese) is given the same strings. and does *exacily* what the computer did (maybe execute the program intunially!), would he be undemianding Chinese? The. rhetoric 4.inly leads to one tinambiguou_i inference *— The compakt does WI undo-2;1'mM a I hini,...* It is thus important to note that the symbols by themselves do not have any intrinsic meaning (like the symbols in a book). They derive their meanings only when we read mid the brain comprehends it. Et goes to say that if the meaning of the symbols used in a symbol system are extrinsic, unlike the meanings in our heads. then the model itself has no meaning. As the symbols themselves have no meaning and depend on tither N.yrritiols whose meanings arc al.so i:...x mimic., 01: SOCITI Iti) he reasoning around tricaningless entities Which ir-42.11' is a m(2._aningless affair! This k the symbol grounding problem.

In the context of the meaninglessness of the use of symbols, Hamad provides a classic example of learning Chitties_ ASRIUSTie you tin' not know Chinese aril had 10 learn it using a Ciiiilem *ri.) Chinece* dictionary. You would compare character by character of a given word and find the corresponding word in the dictionary only to find many more (meanings) written in the iiarne language alongside, for which you would repeat the same task. The process would put you on an endle-is merry-go-round_ I i would be only by trauslaiing it to a language that3[1].Loij uhderttand that your brain can finally per what it Fricari&_ The Chinese symbols in the present ease ate not *grounded* to its meaning. The moral of the example is simple — *You cannot round the meaning of a symbol· with tither meemingien symbols_ Hamad 4.˙11so dies that cryptologists are* able to comprrehend ancient languages and symbols because their eftbris are grounded in their real world domain knowledge as also on ..orne previous language that forms its has is_

Robots form the ultimate test-bed for Al. While Al. researchers have brought forth a reasonably large repository of techniques and programs that are based on the symbol system, implementing them on robots have posed several prohlern_i.,, Though this irriay be beyond the 14:ape of thig book we niu41 exercige caution n it implement in 5.yrnholic Al.. Tar instance an board a robot a Nymbol 'red' has to be actually grounded to inmc value_q rep nod by, die camera or a colour sensor..

Finally one should riot forget that research in Al is multidisciplinary. People have been using AL techniques to reap benthis in a *gamut* of applications.. There *are* still a lot more autrodden paths to be di seeverrd. In the quest 10 find better techniques, the reader is. ihavised lo give imagination a free Tun r that the marginal and the peripheral are ac-Vo rn oda ed without losing the grounding of each symbol.

EXERCISES

- IV- 1% - .... - AIIIINIVE •

1,. Pick 21 SpeC[tiC topic within the scoric of Al and use the 144. antcs described. in this chapter to do a preliminary literature search to determine what the current Azle of understanding of that topic is. If you cannot think of a more novel topic. try one of the following: ex peri systetn:i for some spec ilk domain (e.g_,c,..ancer therapy, computer design, ri nAnc Lai planning), recognizing motion in images, using natural (i.e.., hum aftlike) method', for pro v ing mathematical theorems. resolving pronominal veferences in natural language texts. representing sequences of cveniz in tin:, CT designing a memory organization scheme *for* knowledge in a computer system has on our knowledge of human memory organization.

2, Explore Ow spectrum fmm stalif: to Al-bo.sed techniques fora problem other than the two digcussed in this chapter. Think of your own problem or u,se one of the following:

I Tnuisluding an English sentence inro Japanese

Teaching a. child to subtract integer;

Discovering patterns in empirical data taken from scientific experiments._ arid suggesting further experiments to find more patterns

3. Imagine that you hail been to rn aquarium and wen a sharl..;. and an octopus. Describe these to a child who has never secn one. What rcsources and modulo isms dues ˉthe child use to comprehend thn Tatum of these marine animals?

CHAPTER
2

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PROBLEMS, PROBLEM SPACES, AND SEARCH

!-C fitnr (/rij I :V 2;0 Mart.. *ft dia */slaty'* *FroMwitt kweier*

—Albert Einstein
(1879 195).. German-t)4.mi thucProlcitl pad Nisi

l ii tho chapter, we gave a bric t al:m..6[1.6.km of Iry kinds of prohli:ms. with v. hich Al is. iypicillki ...c.]1 ;is a 4...1.11.3p le of example-s of the uuhrripii it offers 10 Nolvc I hitim.! problems. To build .L.L s....slem11.] !Alive Ii particular problem. we need to do toter things:

I. Dofine the- pry bli,.rm prin:iselv. This WHS.!! iriclude precise specifications of Mini the initial situation is! will Lc what firbill situation.s. cons.tituit! aceeptable solution:, to the problem.
Analyze the problem_ A few very important reLourl....s can have an irtunense impact on the appropriaten1.157% or various pmsible rochniqucs Lir solYing thc pmblern.
1. Lind reprcNcnt iask knowledge that is ni·,..4:12sNary to salvo the problcm.
4_ rbooNc the hest problem•soiving technique.' r.,11 and apply it (them I. tO the particular problem_

n this ch;ipter arid the next, we 4.1isciris ihe first two and the Ilhese issues. Then, in the chapter; in Pilot l I, we focus. on die issue of knowledge representation..

2.1 DEFINING THE PROBLEM AS A STATE SPACE SEARCH

Suppose we start with the probtern staiement "Hay the Although them are i lot of people to whorn we could sLio.. that and reasonably expect that they IA ill do as vve intended, as. OUT request 11.14'1: stands it is a very int:onipletc statement of the problem wc want solved.. To build 1L pruvram that could -Play chc5N,11. we mould first h.u.ve to specify the starting position of the chess hoard, the rates that define the legal moves, and the Ix yard positions that represent a will for UDC side or the utter. In addition, we 31111Ust make explicit the previud.lsly gq)al of nor only playing n ltgal garnr of chess but also winning thc gatne, if possible.

For the pviobivri "Play chess," ir_ is fairly eaNy L€ provide a formal and complete problem description_ 'I1 ma-nit-3v fXi i i ti ffear) he described as an 8 x array vi·hcre each position contains a f..ynibul standing fur tho appro pilaw pitzce in E 41 official elins opening position. \Vt c,:an Licririe us. our goal any heard position in v. h ich the opponent doe!..; not have a letza I move Lind hi...J. or her king is undcr attack_ The legal moves provide the way· L getii D L! from the stale to a. goal state_ They can he described easiViy as a set of rules corisititig of two pail k: left side. that serve.... a Filtern to he maiched against the current board position ;And right that

describes the change to be made to the board position to reflect the move_ There are several ways in which these rule..., can be For example, we could write a rule such as that shown in Fig. 'Ir'',

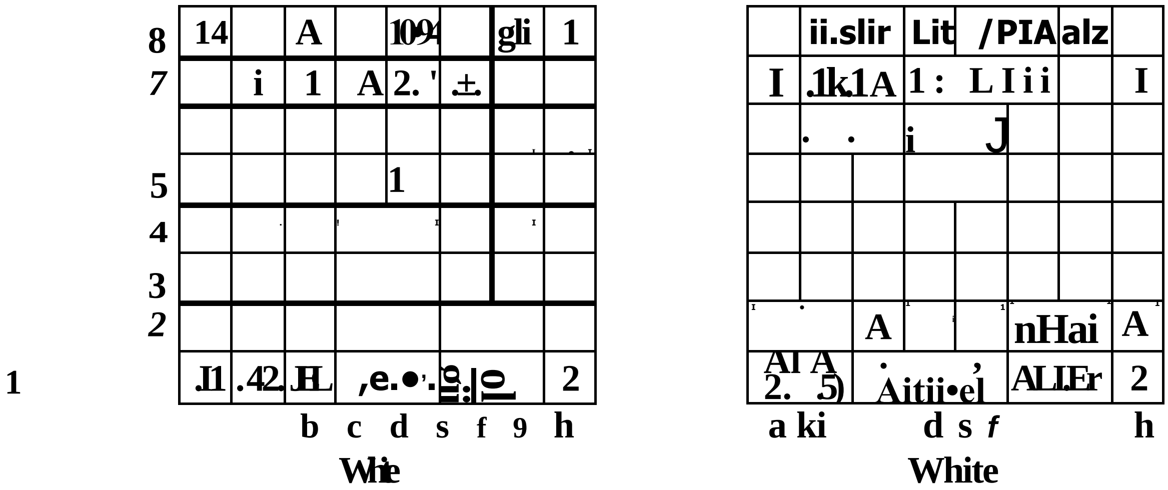


Fig. 2.1 ***One*** **Legal Chess** ***MOVE***

However. if *we* write rules like the uric above, we have to virile a very large number of them si rice there has to be a.separate rule for each of the roughly 10[12°] possible board politicos. Using so many rules paws. Iwo rious practical difficulties;

- **NO perSOn could ever 5,iupply i complete set of such rules. It would take too long and could certainly noi be clone without rnista.kes.**
  No program could easily handle all those rules. Although it hasbing wherne could be LP...ea Ro find the irclevant ruTes for each move fairly quickly. him storinE that many Pales poses serious difficulties.

In order to minimize such problems., we should look for a way to write the rules describing the legal moves in 2.s general a way as possible. To do this, it is useful io introduce some convenient notation *for* destribing pay toms and SklbStitUl ions. For example. the ru lc described in Fig. 2_1, OA WEI] as marry like it could be writtcn *as* shown in Fig. 2.2.[1] In general, the more succipctly we can deseri.be the rules we need, the less work we will have to do to provide them arid the more efficient the program that uses ihem can be,

White pawn at	
SI;luare(rile e, rank 21	
AND	**Inir3o.1. pawn from**
Squareaile e, rank 3i	**Square file c. rank 2)**
is empty	**toSqua.re(file e, rank 4)**
AND	
Square(tle *e,* rank 41	
is empty	

Fit. 2.2 Another ***Way to Describe Chess Moves***

We have just defined the problem of playing chess as a problem of moving around in a *slate spare,* where each :-;taie corresponds to a legal position of the board. We can then play chess by stalling at an initial state, using a set of rules to move from one state to another, and attempting to cad up in one of a set of finial states. This state space representation seems natural for chess because the set of states, which corresponds to the set of board positions, is ;Artificial and well-organ i zed. Tilk same kind of representation is also useful for naturally occurring, less weil-structured prrobierns, although it may be necessary to MC more cornptex strueturrs thacl a

TO be 1.7431111)1041Y 1.111!.rule11tpir41. Fi.Pr rill'met] pieces, which have• ticell ignored.

The eNtre.Trke of this approach Is shown in the first tic•Inc. *toe* prcll:rain of Chaptcr I_ Each (...-ritry in ector Q.oliTospocii.ici. IL) a rale art rati 4)J1. 1111... I rt side. tifi each 02.L.cri gurat I E1 ctpresented implicitly by th.c. iridcx position_ The right side. of each rule. diz!,cribes. the upc...T.idin.n. to be perforthod and is reprrsented by nin:: elenicini vector that ctErre.spomis ti the Each of them...! rules is maximally Npecitic, it applies only to .i sinyle Niard. and, vis is result. no required whcn Kuch rulcs are used. However, the drawback to thiK exirerne approach r !hat the problem solver earl take: ric 4.1.4.:Eitan. at all. in a novel siination. lrr tact, c2.gseritiftilv no prohlrrn 5.49/1.:ing really occurs.. For iliiC-C4.14.:-toe playing program, (hi.,l I R F d prLiblim, since it i ible criiirnerate all the Nickwion.4 tHword ions) Oral may 4 11.:k:I ki. TIM fir Inriom prt11 51121111b;.. this. k nilt Ihq 4.71...e. In orddr to so] VC nevi. problems_ more .E.cricr:11 inusi

1'1 second is ex.c..mplified tly rules 3, slid .1 in kr.. 2..3. Shtltilli [1105 Or should they not ki inctuded i r5 tho)ist or avvilahlc operators') Emptying an tutnicastiroi amount ot v.. aior onto the gintind is cc rtain]y allowo3 hy ;tic pnibluni sti.i[ernent_ BuI a superficial prolirriiilarir analysis. of [1 3e proble3I1 311akE'S it clear doinp eta v ill clever ,..Lbt i1111Y dEPNer [0 a solutinn. Again.. we sec. rlkc L IH k. 111114t dehailV j1.3S.1 the prObieni ItseIC. 4124 Oppi.X41,.'d Li) nil problcm ;Ind sonic. kriovilcidgc solution.

Itu.1 11 and 12 &Lisa aft. a Third issue. To sec to drat thi250 Lepre.seni.. look at the 1w :it tiao Noluition.....ihown in Fig_ ()nee the! ctale (4, 2) is re lied, colivintis h ki'dinne 1.11. 121|14111; produced, but thilev ;tic. in Ow.ii.k...rconv. St} the thiriL.' IL) (Ii) i 111,nr 3 RIM bcfon: IhNE cHri be 4101112, the water 111;it i Areacli.. L]m2 4.2.;il1on jug ri51INIIN: crilphicd out (rtlk r). The iLica bellind these speciat-parpose vuks is to capium the 1':now[edge that can kv usiv,1 this stage the probli2rn_ Thcs..;'.. rules do not nctuully acki privicr to the s•sti.:rn since the up21;:itic.)rts they describe. are already rim% [clod b) ru.L.- 9 the ca,e of rule 1 I and 1 5) rule 5 fin the c.a.s.e of ruk 12). fiut.. dept-nti* on lie ciairo] strare.:4) that is. ustLi for selerliryi i l to tr y [luring pmblem Ole Lhe 111 in.ay klil-gra4,1,,.. perform:mix. 111.31 irk: use (11 th..2...e. rulc.. rimy also improve puTiorrilance ir preicri.mco is siktial casc. rules (as viirc discuss. in Seciiogi

We have row discussed two quite different problern':. chess and thc tivater 11.1.11 problem'. From cliscus siorlc. it should be dear that the 1)P:it Li.terP toward the deslgnora progr:im to solve a problem' must he the crealiiin fit a formal and manipulable. Lte!..cription of the. prol',11.1m 11.; [Ornately, we 'would like to he uhie to write programs I E•i a[can ploducc such forinal descripaorp. 111.11111 infL51 Ogle S. Th i r process is called *f.tpuraffoo[rfir Ntriort. h.* is no! ot tL 1 lwon -uncler:,ii lww lo SLICT1 progrorm. hmt sce Scction 17_1 fur a (14;:cripti or tine prugruni. Lbw pleci: prflbICT11. Until ft h.:curries possible ID) autuniate. tills process, it must hi cifinc hi... baud, however_ For :cimplo prohl SLIch a che:is he *wa[er* jug., this is not very difficult. Tile problem!, art: artificial . h .ILi' i]..5111. l) structured. For oiticr probliins_ varlicularly occurrine, tines, [his step is much MON tlie tw..1., of vecifying precisely 1112at1P% onlersuirid an Eliniglish Szlitencc_ such a specification must sonieliow provided bcfore we can deLiig.ri a program to s.olve the problem, producing, such lx.Fcific'ation i itsclf ven.. hard problem. .A.h.hough our ultimate goal is to be able to solve difficult. unstrilemred prubleins. such naruiral language Lifiderstimpiing, it is t12.1111 1E3 cimpTor problemr._ ...1.14.:11 as the waler.iti..4. prolliern, in order to gain, insigto into tlle details of mileillE)LIN t ha I t u i I 1 Ionia the bor,k for !hie hardL.I

Surnmuziwinig %Oral h;ivc ji.ht said. in ordor to provide ;1 form..11 (tc.scripritm of a problem, we rims! do tile following':

1. Detine stale %pace that contain!, all thy: possillk configurations of ti k,. (511:jc2Clh .44)1110 nne..e.), ti'si2, ı L ihlt 141 c.kfille this KINI.Ce With() Lrt cxpl ii:itly eniurniffa [ins all or UR: SU.NicS ii cuntains.

2_ Specify one or more tai wirhin that space that deicribe possible situatinris rrom which the problem-solving process may start. "Flint states are called ihe

3, Spcciry cm: mom swics that would he aixtriptablc 21:S. 14"Flutions to tho prohlm 11hes zitates are callcd *goal &rates,*

4. Specify a set of rules that describe the actions. (operators) aNailable. Doing this will require giving thought to the following iNsues:
   I Whart unstated assume ions are present in die [nformal problem description?
   - How general should the riles be`.!
   - How much of the work required to fiolive the problem Ai rim Id prot,mi all repi :. ntiii cad i n the rules?

The problem can then be solved by using the rules, in combination with an appropriate control orategy, to move through *the* problem space until a path from an initial state to a goal state is found. Thus the process of sciitch i fundarntitall to the problem-solving prortm.... The fact that. search provides the- ba.si: for I proces& of problem-solving does not, however, incan that other. more direct approaches cannot also be exploited. Whenever possihie, they can be included a steps in ihe search by encoding them into the mks. For exairipte, in the water jug prithlenrt. we use the siandani ariihrnefic operations. as single step% in the rules. We do not use search to find a number with the property that it is equal to — (4 — E Of *course, for* complex problems, more sophisiicatcd computatiorm will be reek,]. Scarch is a general. mechanism that can be used when no more direct method is known. At the same limo, it provides the frarrwwork into which more direct methods for ,solving subparts or a problem can he embedded.

2.2 PRODUCTION SYSTEMS

Since search forms the core of many intelligent processes. it is us.eful to structure AT ppagrans in a way that facilitates describing and performing the Search process. Prvruction sysitms provide such structure's, A definition of a production system is given below. Do not be confused by other uses of the word pmduction. such as to describe what is done in factorie5.;. A production system consists of,

.s A set of roics, mocit fzon5isting of a kitsidepactunni)tha€ dcliarnims the applicability of the n.ilc bLild a right side that describus the opt nition lrr l performed if the rule is appliod..:[1]

I One or more knowledge/databases that contain whatever information is appropri- ate for ihe particular task. Some pans of the database my be peEtnanr...-nt. while other parts of it may plain only to the solution of the currtrit problem_ The iirriormation in chase datalxisms may he tvinichired in any appropriate way,

I A control strategy that specifies the order in which the Rath: will be compared to the database arid al way of rcsolving the conflicts that arisc when sic ',Trail Fulaa match at once.

- A rule applier,

So far, our definition of a product ionsystem has been very general. It encompasses a great many systems, 'Ind Luling our description_s of both a ches player and a water jug problem solver. It also encompasses a family of general producrion system interpreters, including:

a Basic product Lon system languages, such as OPS5 [Brownsien *er al.* 1985] and ACT* [And o. 19831.

- lore complex., often hybrid. systems caillcd *expert sysleAri sheik which* provide complete (relatively spanking) environments for tho construction of blowledgc- based expert systems,.

a General problemsolving architectures like SOAR [Laird *it ofr,* .1.9871, a system based on a specific set of cognitively motivated hypotheses about the ruittre of problem-solving.

This curieentiuri fur the use of and right sides avowal fur furwarti rules. As WC wilt sec timer, man!, IIJ Le systems reverse *the* sides_

Ali of thesc systems. provide the overall architecture: of a rpnxi action system and allow the prugroi-rirncr v..) wri(c rules that iiefine particular probtem5 to be solved. We di 5f,,-uss priAlunion systcrri i...isLIC5 further in Chiiptcr ti.

We havi: now ...een chat in order to solve a problem. we must Erse reduce it to one for which a precise SIOIMIll L,:an he gi'err. Tlii-L can be done by delinlng the problern's sratib.space (includinis. ihe mart and Qoul st9 to si anti 21, Y.L.'t UT opt:Jailors for moving in t hat 5pace. The problem can then be solved hy sears ii n LI I''4 ar ;I path through the spnce from i:kri initial state in. a goal s.tate. The pcocesN of solving the problem can userully ht modeled LS a prod LiCtiOrl Systerit 111 the. rest u r th is suction. wo look at the problem of choosing the appropriate control structure for [hi. production soystern _so tha4 IFic search can he Sys. efficient Lis possibt:.

2.2.1 Control Strategies

So far. we have completely igriorcJ the toe:slim of huw to dceide which rulc: to apply nexl. during the process of :searching for a soluijori to a problem, This question arises since often more than one rule (and sometimes rewor than {}ng; rule) will fluve its left side Tria;cl-E the current sii.l.e_ 'Even viiithout a great deal of thought, it is clear that how such ddeisiort, ar12. made will hair'ff a crtwial inipaci on hinv quickly, and even v...hetber. .1 problem is finally solved.

- *The' ji..-sir 0-elm: woven; of a goad roluroi* ..cfrfirregy *is !hal it* undses moriorr. Consider tigain the water jug problem of the last section, Suppose ...ve implemented the simple L:ontrol straiegy of startling each time al the lop, or thc. list (II' mks and choosing lhe lirs.i jr priicahle ont.. If we did tlini. -...ve woulci never !..wilve the problem.. We would continue in filling the 4-gal1on j u with vhalwr Control strairg.ies that do. TICK Cli.L1SC motion will ncver lead in a s,nlution_
- *The* .vecorid *requiremem rif a good corrirof ararn¡ry is lime il he* p....i.reararic. 1-kre is another simple *Control* smii egy for the water jug prohlerlrir. On each Cycle. chnow at rariclom froin .airicing the zipplicalaie NI In. This 'ti.E Ed c Syr is buytcr it' an the Firsi. 1 r 4: anscs. nio Lion_ h will lcad to a. so] ration cvcninally. But we arc likely Eta 2irrivu at the szirric slab!: several riprics during EFIC pruce,:ss and to 'use man)' rntirc sims !ban are necessary. Illocause the control strategy is non. _;systematic., W1 may explare a particular useless sequence of operators several tirt es. before we finally lincl a .solution. The requirement that a control qr.ategy he systematic 120rresponds (1.1 the need for w;litlr,11 rnmion (over am cr yurs.k... or scir•ierai steps) as well kig fur]sac al rnotiLlill 11.11VE:r the courso 0.1- 41, single step'. Cum systmialic dl mtrul ratan :6.y for.hc.. wailer jug proh le ni is the following_ Construct si tree with the initial mate as its rg.mat. Generate 3[[the: offspring of the. root by applying Each of the applicable rules to the initial state_ Fig_ 2_5 shows how itlh.e tress looks at Ehii point. 'Now for each leaf node, gmerate all its successors. by applying all ttic rulcs that are appropriate. The tree at this pin is shown in Fig. 2.6.[4] Continue this prose so; until some role prodn:eq [1. goal swill.. This process, caitni *brigirdi.or-frrsir search.,* can be describe.2d precisoly as follows.

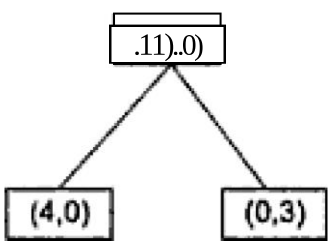


Fig. 2,5 One *LvvEll ola* arcoatti-First -Search *Tme*

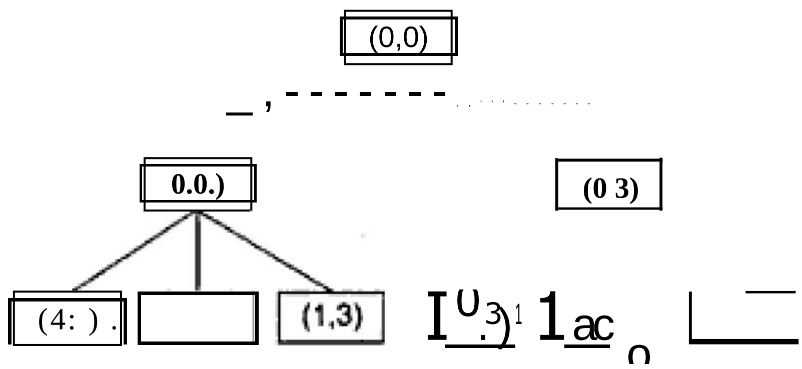


Fig. 2.6 Boat Levey vrr./ Braga - FirsSer.r.re...1r Tree

" Rule ,. 4, I]. Eri12 have t.i.Lerr 4;11ored ill cons.tructilip. the ....Lbk.i.puli litu.

CheSS	ina[crial advantage ot' our side the upponciti
Tra.s.:eling Salesman	the Num of the distance., Far
Tic-Toe-Toe	I for r''w i nWhiC11 we i:Ould win arid in whiL-h [mivi OM: pieCC plus 2 for e:L.1.4:1] 2i1.11:13 row in which we have two pieces

Fig. 2. *Scime Sirnple Hetrejsric f.nunetions*

the purpose o a houristic function is. lo guide Ow s.tmrch process. in [fig must profitable direcikm by suggesting which pill [a fallow first when]ncire than ono is aledil.nhk_ The more accurately the hourisiie function cskiniates the truc iirierits of each no dc in the :se;Arcli Ina- (or g..raph.i., iht mole direct the holution process_ In thc extreme, the he function would bc so .trod Lhat essentially no earth would he required. The system would move directly 1rN a. solution, But for many problems, the cost of computing the value of such a functivil would cidunweiei the effort saved in dtc: pror.vs.s·., Atter MI, itwuuld Ix possible to compule peirkLt 111121.1fiLLCM fiirliA14.1[1 hy doirlv C.:4J-inplete SC4Jrc1 frEyrn the. node in question and determining. whrthri- It 'cads to El Ili N. HI solution_ En general, there is a wade-oil- liciween the cost of evaluating a heuristic furiciion and the saviriFs in search time thlt the functinn proyirics,

the- previous. soctinn, th• solutions Du Al problems wen.- descrit-ted u LITRICring On a search process, Front !he dim:m.04mi in this i[-should be dear lila it colt wore preci!,ely he desizribed [Ls a prucesh *rat-* h e uristic. search_ Some hiairistics. im used to define the control structure that guides the application of rules in the se4.1.rch proc.c.s.s_ Others. as we shall *.e.* will he erioxled in iirc rulo thernschres_ In both casts., they will represeni cithor general Icyr specific wurlid krxmledge that makes the ,soikition iuf hard prublerns feasible. This 1es11N to an way that could define artificial iniellivencv.: the .study K r [ectiniqucs for solving exponcntially pro'1111:Tns polynomial time h.). exploiting 1·;nowlvige iiNiut the problcin

2.3 PROBLEM CHARACTERISTICS

Fleurimit search k a very general method ;Applicable to a large class [Nr problems. It enuompasses at variety of spccific techniques.. each whi di. is part i ctt I arly Qttcctive for a small class of problems.. ln order to choose the most apropriato method or combination. of Trivthogis) for a particular prohlunn, it i. necessary to analyze the problem along several kcy dimensions:

- a IS the problem docompinhable into a set of (nearly) independent smaller or easier subproblems?
- Can.s ! Ut i i ii stups bc ignored or at !cast undone..b. it' they piRlve unwise?
- Is the. problem's universe predictiible!
- ls a gr,.20.1 solution t.4.1 the. pibbkm c5bv11.11.11'; (CI all Other poNsible solutions?
- 1 the desimd solution c_.if the world or ;II lath to a "gate?
- 1'.1 a]fir` zuncittnt of know.lacip absolutely required hi. SOlve ihc problem. or is knowled,ge imporizrit only to constrain the search'?
- Can a cumpu re r That is simply given the proble[n return the sottition.. or will the solution of the problem. require ipterAction between the (....ompi.th:..r :Ind a person?

k the 'chi of this 'A:aim, I c examinc sac h *of* those c.ltu:stions iri greatcr dctail, Notice that some of these gm:vim-11s involve not juNt the slureinern of [he problem itscll but also charactorisrics of the stilution that k desired and [he cirournstances tinder which the solution must t ki place.

2.3,1 Is the Problem Decorm)osable?

suppose mu wawa ;.0 miiye the prob112111 f rom puri az the ex prc. Si OD

P -r1 + + 5irt2*

We can solve this problem by down intro ihree smaller prohlemR, .e.o.ch of which we can 'her FiL ilve hy ming it 74114111 4,.:41.11ection 01 spet:ific INiFure 2.9 shows the problcm tree that will bi gcrien3icd b thc-proce SN prOblernnn_' it *Canby* ex ploited S reCUrSiVe in Legration program that 'Works as follow; Au cacti step. it checks to scc whether the priEb-lent it un is inirricdiakly &olvthile. If so, thvin answer ig returni211 1f the prohlern is not elpiily solvable, the iniqr:irrir checks to Scc' *whether ill earl decompose the problem smaller problems, iii can, it erciinos those. problem ariti coils i i..cel i recurs ivc I y n ti'. rn_ Using. this. tvchnique of pre.thioti *decomposi-tion_ we* can often stall e. very large problems. eaqlly_

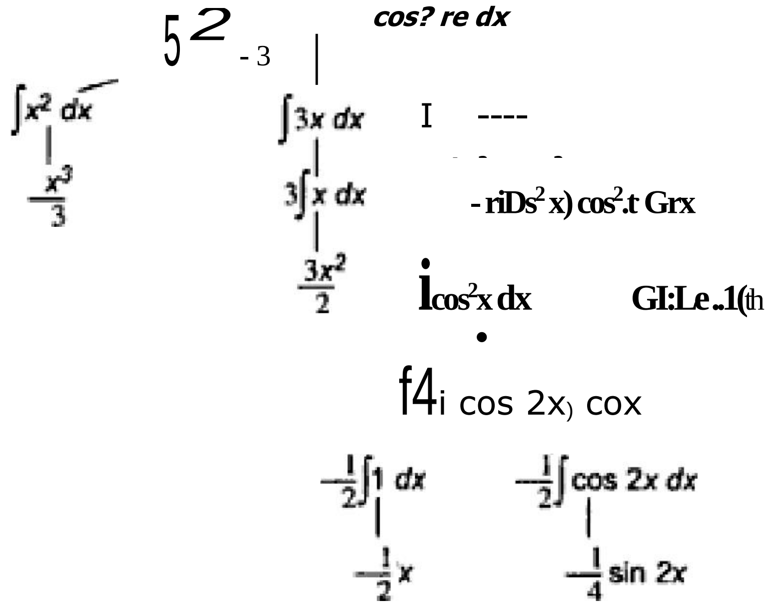


Fig. 2.9 .4 Decompagabie Probirem

Nov.. coirii(lor the pr4.11.11ow illtisirdtud in Fig. 2.10. This problem is; drawn from the dontu.in often roferrod to in Al. literaurc *the Nadu world_* Assume that follow[ng ·1i·Feratnirs are available:

1. **_ CLEAIR (Al [1·flock has nuihing Tab] c) 'pick up and put. it tin au: lahlej**
2. **_ CLEAR ct) Lind CLEAR (y) UN yi rptit x on yl**

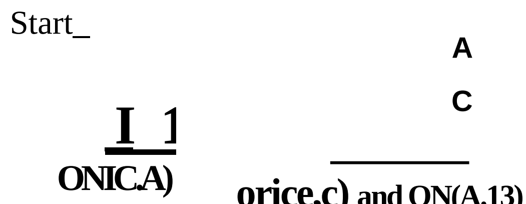
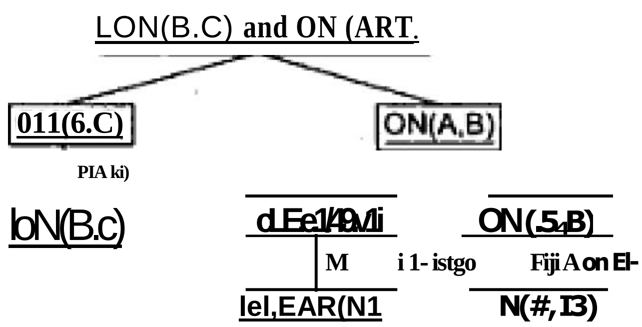


Fig. 2,10 .4 *Simple Blocks Wortd* **Problem**

Applying. lilt lechnique of problem decumpoL,ici)31 to this RimpLe Mocks wo-rli..1. -example lead co, a trc e sucti that shown in Fig. 211 . In rch, goat4 are underlined. Slid e that have aro not underlined. The idea. of this solution is ti.) ccducc the. problem of Exiting B on C and A (311 13 to VI&O :`;cp4.·a· ate problems. The first of the ncw hlkin getting 13 on C. i simple.. given the start slime.. Simply put B *on* C. The _...e_conr..1 LIFT 0 2111 is not cluii p I _ Since the only c3pelitl.4.)ts we have us to pick Lip .single blocks at a 'lime. we have lit clear off A *hy* C before we can pick up A and put ir un B. ·17-ii: can easily he duce_ However, if we nov, try io combine the two subsoludons into one soluilion,. We will Regardless of nne we do first, live will no[he .ii.13]12. in do (he second as .1.102 kid planncd. this problem., the two 611bploblems am riot independent. They interact and the qe interactions muse be oongidurni in order to arrive at a..6olution. tor the entire problem.



Fig, 2.11 A Prot] .see Solution *far d Mocks Probictr;*

These two exarnplos, symbolic integration arid the. Hocks world, illustrate the. difference hetwocn dccompoisuble and nuridocompo.sabk prublems, In Chapter 3, wc pre-sc.:A a specific algorithm for problem decomposition, and in Clicapter 13. wc look al. what happens he decomposition is impussiblc.

2,3,7 Can. Solution Steps Be Ignored or Undone?

Sluivosc iiro trying, ki pV0Veza nialiherililtical theoPuM. 11/41.74! priXcral by p-CIA inga kmnlil that wt. thirik will bc. use Eventually, we realize that (hi:. lcrnrna is no Ih.clp. at all_ Arc tve in truublc?

Nu. Ever). t hint we need to know to prove the ihcorcriri is still true and in me rnc irk'. if it ever was_ Any ruks tliat hark e been applied Lit tiw outset can. still Ise applied. Vic can just procted al. Nier IlwEve the first plkice. All we Kaye luist i ihe efrorl that vi expioring the blind 41.114,!y.

Now consider a different p14.3111en.7.

The S-Fuzzle: The K-pi.17.7.10... L.4.11.1.kirt• lcu.y rn.1.41-;:ich qty phut-d, eight ....guare riEr4. The lermirlidh2. !...iluare is. um:men:kJ.. Each h.a.· i rimilther(Init. A the that fib adjaLent [1)c:blank. ..}.1.J.;:c cal I_slid into that NI e. A gdinie Elf ;I iErgply:Lilian uni.13 :.;Recified TL-...e44c.ilr] i' to tranr.formllrid: Nu:Li-dry raNithin in.to the r03] pusilivo i:py tiIidirrg it5r2 riles around.

A sample game LJS iris ihe S•Firtzle is slimy, it in rig_ 2_12. In at to solve the 8puzzle, [nigh' make a NiviLT move. Toe eximple., in the game sh.c.mn [, ahluve, iniyht skirt by11d ink tile 5 into it empty space. Having dun Thai, we cannot diktopc; our rnimi and iffiniediatcly 6.1iirlc tile 6 into Ehc- cmply space since the 12m ply a.v paw will essentially he moved. But we can backtrack and undo the tirbt move.. ?Aiding. Igo 5 io where %as, Thicn we Can n !He CF_Pielistakes Cain b recovere,n1 from but 114)1 quite as casilly in the theure-nr-rroviq.. grub kilt, An addiiiunal :Lite") itti to i brz prz..rforrricd to undo cacti ini.:orrcct stir p, whet-ells -iction rcquircd. to -lynch)" a uselcm. lemma_ In addition, 'h: control mechanism for an g-puzzle solver must keep track of the order in which 4lperat1orr; are peilormedl so that the operations can be turitione one at a timr: if neoes:siiry. The conitrol sing:lure for 13 dieorern prover drielii not ;..ieed tn. record all that information_

Start			Goal		
			I	2	3
	8	3			
I					
6	4				
;	5		7	6	5

Fig, 2.12 Ari Exunipie the 8-Puzzle

Now consider again die problnn of playing cheNs.. Suppost proErani inake.:% a stupid and real iics it courle of moves later. It cannot imply play as though it had never mat ! i he stupid mold c, Nor can it sirnplv hack up and start the game over from that point. All it can do is tc.) tr.,. to. make thc best 4.i . the current situation iinLi *go. E11 from* there.

Thvc..12thrce problems– Theorem proving, the ftpttult, and chess—illustrate the aifrerericts to three i mix irtini 4 lasses of ilrub lems:

- 1.riorable theorem proving'', in which solution sleps can he ignored
- Re4Lor'cu11110 in which soluiiim t-ie undone
- 9 Irrecoverable (e.g.._ ch,mcs). in which!....cilultion step... cannot be undone

These Ihree definitions make reference to the steps of the soluilion to a prroblem. arid thus limy appear to chiLtacieriec.. pro-Jul:thin mistons for !..101.1..ing prthilvrni rather (hurl the prnhlem formulation of the same proialL:m would icad tit the problem' being characierizcd dill-p.=11y, Strictly spe;iking, this is true. Hut for a great it problettn. Esc re iN only one (or a small number of essentially equivalcrit formulations that iruirl.irall)· Liescribt the problem. This was true for each of the problems ued examples above. When this. is· the case., it make:s sense to view the recuverability t)1 a probler . a' equivalent it] Ilhe rtcoventhiliiy cif a. natural 11.•rmillaiion of

•1e to.Tpvcrobility E.)fp, problcrn plays an important role. in clo.crinining !he ihLt control structure necessary for the ignoralblu probicm_s cart be solved using a simple cuntrc.)I strucAuiry that nc•er hu.clarac1;!-;. Such a con[rol s[ructare is ea_sy to imrkrnent_ Recovuahlr, (.-ark he s.4..plved by a ',lightly inore complicati_Ld control strategiy that doe., sometitnes make niistakeN. Backtracking will rr...N..1-sh.arlitO recover in ii n bud' 111 iota taw control str-t1.4tirc..! must he implernonted poNh-dovkil uck, in which ckeisiori_s are re.cordcd in caw tihey need to be undone later. Irrecoverable problems_ on the other hand.. win need in he 5 01 V ed by a systcrn that expends a great cleat of effort making each decision since he decision must be final._ Stnne irrecoverable problcmA can be solved 1w reeoyffable style methods. lista in piannfng proce.ssi iii Mid) Lii seciucnct i..]t"..slccrs. is amilyzed iii iidvancc tL discovcr witerc it will lead before the firm slop. is actually tikrz.n. Wc discuss nem the kind!, of problerni., in kid-rich this k.

2,3.3 Is the Universe Predictable?

su.ppoN2 that we larn pi ay jug with the S- puz It Every time we :mike. a 11101:1'. 4r know curtly what win happen_ This mean s that it is possible to plan an entire sequence of ma ·es and be confident that we know v4 hat the rcsultin.2 state V ·1 be, 'Vide can 1.1'Lid: planning to avoid having to undo ;Lau:ill moves. although it will still h neeess.ary th, hac·.k·troct past those one at a tine during the planniuE. process. Thus a control !Arnow rc that ilkporls 11.acktrucki will be

L31 gik1111JS 4111.12V1/1Mil th i. 8-1)141:111.12- h i pli4nning proc-vA' May not 1.112 possible. Sup.p4I've VII I: ti plas· bridgc. One of The decisions we will ic·) TN:Lk:i which *i2* arid to play on thc first trick. What we would to dui Is to plan the 'entire. hand before [hulking that first play. I Lit Bow it is foil possibk to do midi planning with cerhaility since We' cimnot loriLm ex:Act!)· he,211` Al the c.iirds arc. what ihe phi|. ers; will do on itwir 'urns, The hicst we Call 'Lit) iptVW[gatC vcra pimp.. and use probtahitilits of ou[coriles Liu chcww..c- tt plan 'hat has the higl·icsi estimatod probability of lcading tc a gui.a.d1 scurt!n I b the- hard

Thine illustrate the difference be1...y.1_42-n certain-o titcome le} and 11 riccriui ri-ouworne brjdge problizrns.. Orie way or plarming is thiLit it is problem-solving without rc-c..dhack from the environment_ For solving *CC* nairl-outeonio problems_ this open-loop approzich %%AI work rim! rcshil[of an a.cli c.iin be piedkted planni112 LP-121.Imgchlkhriik. ci]xbrithrn, that i trivall teed to lcn d. solution. For 10[14:421 rtin-orit..21 H1re prc 511)1C UN, liowc.ver,*lining. can it —helm 42.,2-11 crate tl soqi.pcnct: of opersiors that has a good probability of 1.12...itliiirg to a solution, 'a) oIve Sill:11 problems, vire ilecd for ;1 process of *plan rerfgon to takc* ploce the plan k carried out arid the nocnsary feedback iN provided_ In uddition to pr i vi di ng gtirantev of an ;iota milution. planning iur u.ncerhain-raiii [come prublemn has 1.11,2 · ithed it is (ii[en very expenqive shrhee the number 41.1 soklion pi.oliK That need tiF h explfired

t *MIal]y'OrMilt* thc, nuimtihe` IL1 f poirns ;it c·arinot

The labt two problem characteristic!. *we* have di-ig.i..1*;*;e4.11, iginon.thIc vcrstli. roc over:Able in¨ccovcrablL,!. and certain-outconic vcrso!. unceriain-outconle.. into raLi in an in tc.n::....ting. way_ .As DIrcu.dy been mcnitioncd. one way to irr.e.erovuraible b terns is. to plan an entire soil ution b• [urn ie.¨tub:irking on an imp] Li nee tai i on f..)f pkin. But alb. planrling process can only he iluite kiTectively for 6:E.:mini-Lim too no Thus (me o the hurc.le:L.t types Of problem., til solve k M1 e irrr..b.cove.rablth. tinvvrtniii-ntilcorne. A Fink: cvainplos 01 such proble ms aro;

- Playing. brid2e. hut can kill vhe h; the lable acciaraw csiiniutc.... of the probabilities of L:15cli of 1 1·14 ixIssiblc
- COrarolling a robot The tuttcome Iv; uncertain Ibr a 'variety or masoiri.... 54.1i7ic¨one might nurs.c: sometling. in tiro the path or the arm. The *:Lcars* of th• ann might Mick. crnir LIM Id cause thc. air It to knock ovcr a whole stick of thirigN.
- lliwyer decide hiya t4.1 deren4 his client against a nutnier oharge. Herr4 we probably canclut even li.st all the po...:sible outcomes. much PrOhilbili6CS.

2.3.4 Is a Good Solution Absolute or Relative?

Considur the problem) of iuti...vcriET Lased on it such (Fic

. :..1.1.reus was

\kircu: ·,..c7.1s 1[3]onipeiart.
1%.14.7-reu:_ 'bry;,r.i born in 40 A.D.

4. Ail mr.fn
5_ All Rompeia_ns died %%hen ii.okano erkirpted in 79
6. 'ii ink hk.in 1.50
7- Ii is now 1'19] A-D.

111.1.fill a7 7 U.. • z ' t 7 . . . _or r.0

Suppose we ask the question Is Marcu..:, ;Ali\ e'?'` By rRm sc ❑ti n L2. Cach 01·1.19·9.2...14.cis in a formal languagc. as predicate and then using formal infcrence methods we can fairly easily derive rr1 u.nswer to the qu&stion.[7] I t7 fact, either of two reasoning pHtlis will leml to ihe ag. shown in Fig, 113. Sint.. all we ku·e interost.cd in is the ilinlywcr to the toe,tilari, it s liot minter which pallh 1. foilov, If vie do follow onie path successfully in the answcr, then.: is nu rcasuri to ri bark arid. *see* if some other path [ni?ht also lead to a solution..

von

Man:us was a ITILM..	axiom
4_ All men are mortal.	it)M *4*
8. Marcus is morial,	I *4*
3, Marcus NA as born in 40 .A.D.	axiom 3
7. It is mil.): 199! A.D.	itic.i.o!rt 7
9, IMari,lis` age is 1951 years.	3. 7
6. No rmirial lives lonvier iliac 150 'fears,	
10. Marcum :ii dead.	S. 15.. 9
(JR	
7. It is ni-Pv.. 199] A D.	i.i.A.join
5. Pal Poirlxians died in 79 A.D.	ax ion] 5
I I . All Pornivian...; are de4.1.ii now.	7„
2. IVIdruils. wits. a 1"4111rpeiiiii.	axio Ml 2
12. .Marcus is dead.	11. 2

Fig, 2,13 Tom *ways cif Duricith,e,1 Mot ittorco.* *Dead*

But nrpor- consider aErain the travoling sali...:siman problem. Our goal is to firki the shurtest mute that visits each city exActly 011CM_ Supprise the Lilies to be visiArd arid [fro distances. he[woon U112111 are as s.hown ill Fig_ 2_]4_

	Boston	New York	Miami	Dallas 1	_ .S.F._.
. Raton		2.50	1450	17(x)	3000
New York	250		I:IVO j	115EKI	"291'13
Mizn9i	1 1:-150	1241.X1		I tial	11011.1
DmIla...:	[1700	151M1.	1600		11700
S.F.	' 3000	. 290.}	31011.1		1710{)

Fig.. 2.1.4 ein *instance of* 01E' TrETVeirir?,e) Sidie-SM Gu Prublierrr

Uric place the, saksiman could start v...Boston. lit chat case, one path that mipht be followed is the one shown in Fig_ 2. [5 which is 8850 milts lung. But is (Ili!, the to the prohlern0 The answer is th..,i(W e canrint be sure uriles.s: we .iLls.o 1 ry all 4,1ther 1).151.11S It) Makr2 t, r [11.0L 11.11 no {if than is sh itri c}r_ In (hi% 1..7411S1:, be see n from Fig. 2.16, the firm path is; definitely not d solutimi. Ui Eh; sulestriart's prublem.

Thy sc two cmumples. Ulu:inate thk... difference Scimitar anypath problems and bes(path problems. nest-path problems; are, in general, carnputaiimmlly imrder than an) path prohlems._ Any-path prnhIcrris mil alert be solved in a reil:sunable -irriount of time by u.sin hcoristics that !-..ogge·..i 12.Dof.„1 paths to expkne. (See the discussion of sc:arch in Chapter 3 for one wiiiy of doing this.) 1.1 the heuri2itics. arc not perfeg...t, tltc search for a solution rnav not be a Ltiro2ct a pal..,sible, but that doe% not matter. For true best-path prohterns, however! no hturistic t hi t t ald possibly 11t i tlic br.:Nt Ma I tats t fn czn hr used. so a much more exhaustive arch will lbe. periclirried.

[7] Of coursc. rcpresenting thcbc Lii.;iiurnen.I..seta Clot a rrireciKeiical procedure could cApIniE thcm ti ui the 4.[Licsticyri. also ret.v.tirr...4 the explicit uf other facts. such as. "cit.:A implics nEwt alive \kir rat, ihi, i>> Clr.i.pler

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(1501 0)
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(120D)
Miami I
(1450}/
-stark
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Fig. 2.15 One Path or: wo],w arc. Ciffir....

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Miami (1450)
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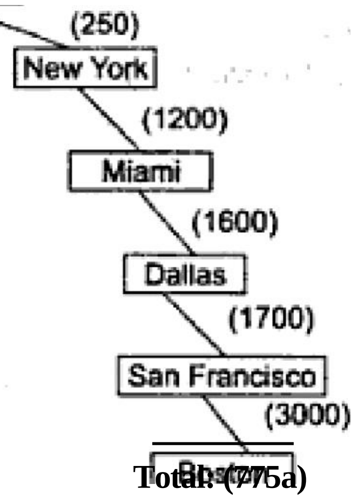
Total! (B850)



Total: (7750)

Fig.. 2..16 7147.1. Puth.;mi' Cities

2.3,5 is the Solution. a State or a Path?

on der the pin/4cm 4.51 finding a wit....iment inielpreiatigm ror illie

[lie bank president ale d iii2;11-131 1ms,[a !.,.1].H.1 with thlf fork_

There are swctual comporierukti f t hi..ientenee, euch which., in isolatiun, muy more than Oirie inierprelikliron. Hui Eh: 4...ornporionts It1kl.t form. CCALlient h e • 1.111-1 :411 they constrain e.cich (51.1itr'S itnerpreialiOni_ SOITIC of 1.110 SOLIFCC5 n I u.nthiguiLy in larrrence .are thc following:

The ward "bank" male refer either to a financial instinition or to a side of a river, But uni one of they.: may have a president

word "dish' is Ow ubjel..1 oldie "cm. It is pos...Able tlia.d. a dish likia_iica(cn. But it is riNore likely that the. pa.A.o. salad in the Wsh was men..

- Pasta is. a salad coimining pasta. Hui ilicre are othoT meanings can he formed from pairs or nourrs._ For example, dog. foirid does not normaby contain flo2s_
- liar phrase "with the fork. could modify several parts or the Nerik..nce. In t Fi i case. it modifies verb "amt,'s But, if The. phra....ic had been 'with vegetables.," then the modification structure would bt different. Arid if' the phrase had been "with her fri.1211cis thn milli:tore. would be different gtilL

EliecausL• Or au: in,(12:rac [ion iIT]10113g i hC 11 tC rpfet.a.ti.Orli of tic 42 tucThis thiN SZIlre.oce, &Mlle Seart h may be required to find a complete Interpretation for the sentence.. .E3ut to solve the problem of finding the interpretatiun we need to produce only the interpretation itself. No record of the processing by which the interpretallion found is cio.:4.ssarje.

Cimtrast with die wattr jug problem. lieu it k sufficient tri. repoti that have solved the prthiein ill that the final state is (2, LPL 1" 1ir this. kind Ed problem, whai. vim really irruist reporE is net the Irina! $.1,318 the path that we found to that state, 11 itis a statement of a solution to this problem most be a ......e.querice operations. (Nometinies Called *apethe)* [hat produun the final stale.

Thrise two. examples. uzioral 'angina:go ondors.tindLng wind the water jug problem.. illtr-itrato the difrerkince bawern probiLms whose sulution i' a slate of Ihe world and problems whosic solution N a path to a same_ Al one level, this difference can be ignared and problimis Can be funmilated as pries in which only a Auk. k required to be reported.. I i WC do this for problems. such n the water jug. then we inosi redlescribe OLIT StiiteS SAD t1 t each tie represents a pa i pall' i 4.1 Sr rLliti on rather than j um a sin k stale the world_ So thi Liu eStiOn

- Solilary, in which the con¯puRr is givuo a problem doscrip(ion and produces i:in answer with no intermediate communication ;und with no dornand for an cxplanotion of the n2asoning prmess:
- conversatic vial, in which there IN. iniennledliare .L.i.iirirnunication 11).121.0A:cm a [J ₃i. and itw carnpuiff, either to provide addition.;31 as.sis.tancic in. !biz :i la or to provid4...¯Ackliti4.mal inforrnarion to alit user, or both

Of course, this distinctiori is not a sixict one de gibing particular problem dormins. As. *lhiC* jkiSt 7...h.Gwed, mathematical Ihe-rirern priivirIg could he regarded as either. Bui fOr n Tranicular Atli oat ion, one Dr the other of these types ·.ii·sysrerris wiil Lis.ually he dc...ireld ;midi that dt..ei:don 'Ain he i irifvt tam in the choice of a problem-soNing method.

2,3.8 Problem Classification

When -actual. prohlcms ¯cure examined from thu ixii.iht or .....:ic...v corliii tif ihesi..: Liu ehi i on s.., 1.1. bo,:ornes a pprerm. thai thi..n.1 u.re several broad clr.iss.cs inio which thc.:.. problcmi. fall_ These classes can each tic aysociated with 1.1. generic control strate.gy that is appropriate for wily in g (lic problcm. For examplc. consider h c generic: problem nf *classificalfon. The* task here is to examine an inpul Luid 1..hcn ticcide which of a sci ni known classes the iriput is an instance of. Must di.vnG.5sLic.t....iNkN, including medical diag,no!;.is as well as diagnosis of faults in mechanical devices, art i.....x.airiple.i. of classiTIC4itiOn_ Anoilier examrik of a F.rieric sirruccgy i pyipeyse flab? re...fitie. Marty design and plzinnir)2 proWerni, can be attacked with this. strategy_

1).cpcndirig on the granularly... ait +.1.1rlich viie attompi Li) cl.T.K.,!,ily probliAns and control straregic..., ...VC *J* nay come tlp with different. lisLs of generic ta....ks and pyrkeedurei- Sci Chandrasekaran 1119861 Und McDtnnott. [19881 Fur two a pproahe.:4, to con stnicting arch 1156. '11 to iiripartaint ihi dig to remember hen:, thouzh., since we are .il.lout to ClilKart "Ii a discUSSiOn or ..;1 %rainy of prohk.in-solving *11112[114¹th ᵢL/S !hill 111101·4,` is* no one single way of solvinr all problems. But neither 'mist each nevi; probit.rn he considered totally .r2/3 initio. Instead, irwe. analyr.e our problems carefully and sort our problem-solving methods by the kinds or problems t'oir which they are '!-Juitable. we will. be at to bring to each new pmblIcrii much or what we havo teamed from solving ol her., similar prohlem.;.

2.4 PRODUCTION SYSTEM CHARACTERISTICS

We have jusi. cx.aminod a s.d. ill· eharacterimics that distingukh various classes nit problems. We *have* also ar.g ued that Notltio its n sy-..te n I% arc vi good way to descri iv the op:rat ions that can he performed in .a search for 41 Wilding In 41 problem. Tvot¯E questions vbe tnivIlt insolubly zft.I.... at this point arc:

I. Can production systems, lil·.. proble mi. be described by ii Set or chuacteristicb Eiliat stir somt light on how they can easily be implernentuir
2. if ......a. lelLhat relationg.hip. art. Lhere betvi. eel) pfoNcrn ·1....-pos 4.tritl ch• types of pre 1-&Action 9. stern!, hest st.iitcd to solving the problems"?

Ille answer to the First quoilim is yes_ forulider the following deimitions c.)f cipNws. of production .systerns.. A *rrre•are.i.trir prt iduc I i an .[1];2.·v !ern is .ii, prildklellicM* s)slerir in which ihic appliCation or a rule never prevents the latur appliwaiion of another rule; thait could aliwii have. boi:41 applicd al tlic ti iliac the firm rule was seleckqi. A *rrunintinotonic produer ion Postern* is one in which [his is riot true. A *paniany corninutaiiVe7 131190ⁱi1CtiOn* .sysrelir is a production system with ihe propely (hit if the :application of a particular .sequm:.-e. of roles transforms state .r into !init.: v then any pormulation of those rule_s. that is allowable (i.e.. each n,fle's preond.itions are satisfied when it is applied) also man s.forin s. stale x i mu slum:. y. A cfmninscirefice *po¯iduciiim SySieni* is a production symern that r both monotonic and partially commutotive

[3] This corre!prinds to the definition of :a commutative production. syitehni g,3... en Ii NI.ISSOJ1 I C901.

Alan' .1:1m-li-alleor-lial I-1. 1 WEI

The signiricartce of these categories or pruditetion .hyht.einsI ie in the relationship ti-oween the categories and ti.ppropriuie implemcmation srratellies. Ilut bcfare cligeusgint.2, that rtlaition.ship.. it may be helpful to make the mmningsgat the dotinitions ulcarcr by showing how they relate to specific problems.

Thits u arrvipie cli che queslion above, which as.kei..1 whether there i. an interesiing relaiiorKhip heivilecn classes of prodki.ction systenn_s and Ehiise!.; prohluns. For any SA.)1 problem.. the exist an in number tif production. systeAris that doc:ribe ways to find solution)._ Some will be in re natural or efficient than tabu rs. Any problem [hat can be solvcd by an priyinctiun system earl bc... solved by zi commuuktive one001111- reSirjA,:teA ci:INS), but thQ i.iirriniintativt. One may he s.ri unwieldy to be practicu.ily uselenis, CL use individual in represent crnire scqucrices or applicatic.ms of rifles of a chirnpler, noncorrimetaitive systent. Sk} formal seriht. there is no relationship between. 1k..inas of problems .iinct kinds or production systems since all problems can be !...o.b.cd 1-iy all kinds of Aystems. But in a !indicth there definitely is such a rr2daticmchlp bet' een kinds of problems and the kinds of s.ystems that lend tlhernselves naturally to describing t1io...;4.3. pi-oh-lent-lc. *soc this,* LI us look a few examples. Fig. 2.17 Nhoi..k.s four riaregories. _sys(tmoi produced try the I c dichfitomies. monotonic verFus nonrannoionic *partialiv*

	11/411.111(11oric	N:130[]101U C
comtnutath.e	it europ proving.	Robot navizatinn
Not corrimuiati'e	Chemical syntheiiii.	Bridge

commuLativ verus.

g.. 2.17 The Four *Categarfes of Prothaliorh* Systeri.

nonpartio.111) commutative, diong ith sonic prcEblerns that 1.4L11 naturally be solvci.1 1)). each iype of system. The upper lef corner reprcsenu commutative s.ysternN.

Parti;illy cow mutati vv, proLlu:.-tion ;UV1.1As'lal -1011%111V ii2norillhic problems. This is. ric)i surprising sin o: [1]4: 4.1r the Lwvo arc omvellijally the same, Rut recall that ignorable problems tire those for which a natural formulation lads it' solution. strop; that Can be lenored. Such EI natural frinnulation will then /IC a portially commutative, monotcNtic system_ Problems that involve ercaling new things rather than ehanLiink!, old ones are z.encrally iLinotable..-Ilieorezro prrI w int! _ We have. described. it, i one ex.:ample tar !LiLICK a rreutive procch.s. Mak.in2 klekliiciions from some "mown ram% is a !.iirnitar creaiive process. Beath those prixesses can camil.)• be iniplumented. with a partialLy commutative, monutonk sysicin.

Partially C011111atitZtive, monotonic- production symi:ms are important from an irriplemewAion standpoint because they can be implemen.ted i thou(I tie ability to bar:lama Lu preiviou& states whet) it is dint over that an incorrect path has been follovied. Although It i <t1 c]1 io implement such systems with backiracking in order to guru-andel: ti sysioirmiic tiw databaNe mpre:Lienting ihe problem stale need noi restored. This often results in a4...u.ci!..idcrable increase in cfficicncy. panicularly br.,C rinse since the database will never have to be restored. it k no; necessary to keep track of where in the .1·24.-irch process every change was. yriaik.

'Wehivve NrEially c4.1.111101.1iative pr.Lidur tioli sy....burn.... that T.irc also nLoriotorlic_ llwy are good for problems where things d.ci. nnt chungc-, ncvi thin gct crcared. Nonmonatonic. pariially commutative yclrernit, mil the other band.. are useful for probionis in which chwges. occur but eon be reversed arid in which order or operations is nut critical_ This.i usually the case in physical itanipulu.tion path Lem', such as robot riavi gai ion on a flat plan e,,Slippc.15.e that a robot Ii the following operators: go nEIrth (N·), go east (E), kto south (5). arid g.0 wcst (W). To reach its goal, it does not rnaurr whether thc robot cxccutes N-N-E. N-F.-N.

on how the op.12riatorsuri: choscri. Ehi8Plizzli2 arid thL. blocks world problcm can also he considcncd partially commutative.

Both types of partially commuititive production systems aro sigaificant from an implementation point of view because. they lend to lead to many duplications 1111 individual state., during the gea.reh procesl. This is discussed furalcr i n Sc.ctinn 2,5.

Production sy,stems that art. not partially commutative are irseful for many problems iii which irreversible changes occur. For ex consider die problem of derxraining a, process produee a. desired (..temieal coil-wound. The operators avail:1111c include such things as -Add ric ti: the pot' or "Orange the temperaffire to I degrees.- TheNe Liperators. may cause irreversiblt changec to tht potion being brewed. The order in which they :ire performed can tie very importarit in the final output. it is possible that if *x is add to y*. a stablc cotripotLnd will be formed. so later addition of .z will have no effect; if .: is added to v, howl! *VCIT*. a different stable compound may Ix formed. so later addition of will. have no effect, Nonpartially commutative production !...yAi:rris. are less likely to produce the same node marry limes in the search process. When r.iealing wilit ones that iik-i.cribc irreversihle p[43.cesses, it ii poirticLihrly imrportasit to make correo the Ii Est i i ri lc, aliliiaugh inilicitniver,c i Jil rLl ic lc, planning can hi: w make !hal les!, important.

2,5 ISSUES IN THE DESIGN OF SEARCH PROGRAMS

Every Nrnrch process earl hif viewed as a traversal at a iret stiveiLlre in which each node re.prestow, a. problem state. and each arc represents 4 rkti41.1011hilip htiv.4_412.31 ih-c: slates rtpreserilud. by the nodes it connects_ For example, Fig.. 2.18 shows part of a search Ibr a ware r jut!. problm. The arcs have not bccn labelcd. in the Fig.. but they corNspond r~ particular water-pouring oper-..i.iioris. Mc search *process* must find a path or paths 1-irough the tree that uonnect an i n i ti a I t s with one eir inore final states. The Iree hat must be searched could. iri consirucicd c i r i1 cry [ire.). from ihc. rules i Eta ficlunc. allow:111k miives in [he prrAhlcrn *Space*. But. in practice., impst of it ncver is. It is too large and filoLdi of it n•cd never he explored_ 1pste_ad or firm building tree eplicitly and bin searching it. most search. prop,rairrc represent the- tree *irtephrilly in* [h.c. rules and gene-rate explicitly tinly [Hose piarts dal ['icy decide RI. exploro$_n$. Through4)1A our discussion of search methods, it is importantlokcep in mind this distinction boween (4.3) {CO) I search irces and the explicit parial scant actually com.c.tructed by the search prograni_

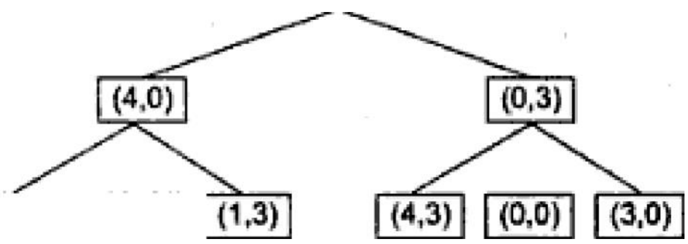


Fig. 2.1a A *Search Tree for th* e Waterius Problem

In the neNt chapter, we pre!-ierii. a family of general-ptirpose search techniques. But before doing so we need to menl ion importani is.stLes that ari!,e in i111 or them:

* The directifm in which to conduct. the Nearch *(forivtali versx;* badwend reasoriingL We can searcb forward through the state space From the start state to a goal vi.c. can ,search backward from the goal.
* [Wilk ruk 1. Prvidlicti I. lin gystenu., [ypic a] ly spend nooLbt of their time looking for roles to apply. so it is critical to haw efficient proccdurcs for malichin.FP ru.lcs against states.
* [14:0.1,' to represent. aid] node or the search process (the knowledge *rcpresenrafivri intibfcrio* and the *firaMe*problem). For problems likc chess, a node *can* be folly Npresented by A simple —r y_ hi more Climplcx probluin soIvinE.r, huwever, it is i,rlorlicient antilor itnpossillic to repre-serri of the facts in the world and to determine u.111 ;if' the side etTects an motion may have.

We discuss the knowledge representation and time problems further in Chapter 4. We in vest ip,ate matching and forward vers..u.!.: backward re-asoning w here wo return to productitin systems in Chapter 6.

One other issue we should consider al this point is that of Neurich trees versus search graphs. As rn.entione.d. above, we can think of produciion rules as gencraiing nodcs in a se.arch tire. Each node can he exparded in tam, generating a set of successors_ This process continues until a node representing a solution is found. implementing such a procedure requires little bookkeeping. However, this process often results in the same node being *generated* Ds pail of _.+.1.:veral paths and so being processed more than once. This buppens. became the search space may really he an arbitrary directed graph rather than a iree.

For example, in the tree thciwn in Fig. 2.18. the node 4,3)., representing 4-gal1fins or wailer in ',me jug and 3 gallons in the other, can be generated tither by first filling the 4-gallon jug and then the 3-gallon one or by filling than in the opposite order_ into the order does not matter. continuing to process both these node would be redundant.. This example also illustrates another problem Mat often arises when the search process operates as a *tree* walk. On the third level. the no.cL (0, 0) appeam (In fat.-t, it appears twice.) But this is the same as the top nods or the tree, which has. already been expanded.

Those two paths have not gottcn Us anywhere_ So we would like to eliminate them and continue only along the other bnAnches.

miadasiimaim
. An' dicirel
PCI*
irrilteirligeo
E t *ce*
1(0.3)
1_4CI)

The waste ofeffort that arises when the same node is gvnizraekll more than one': can be avoided, a t (hid price of additional bookkceping_ instead of traversing a seatch tree, we traverse a directed graph. This graph differs from a iree in that s.everal paths may come together at :,,. node_ The graph corresponding to the tree 01 Fig. 2.1 S is shown in Fig. 2.19.

Fig.. 2.1) A *Scorch Grciph* PT the Wove· erN *j* *ug* Prohli

Any tree search procedure that keeps tracl.; of all the nodes that haw bccn generated so far call be converted to .a graph search procedure by modifying the action peritornal each time a node is generated.. Notice that of the two symcrnatic !search procedures we have discussed so far. this requirement that node_s be kept track of eft met by breadth-iim search but mot by 41....pthfirm search, Rut. or course., depth-first search could. be modified, at the expense of additional storage, to retain in criernory nodes that. have been expanded and then backed-up over,. :Since all nekleS Mt riced in thc search graph, we must DSC the following algorithm instrad. or simply adding a new node to the graph,

Alistoritiurn Check Duplicate Nodes

1. *Examine ihe se* of nodes thEti have been crewed so far to see if the new while already exists..
2. if it does not-simply add it to the graph just as for a iree.
3. if it does already exist, ihen do the following:
   (a) Set the node that is being expanded to point to the already cxiaing.-nuidc corresponding to ils Successor rather than to the new one, The new one can simply he thrown away.
   (b) If you are 'keeping traclk *of* the hest (shortelt or otherwise least-cost) path lo each node, then check to see if the new path is biter 4.1T worse than the otd one. 11 worse . do nothing. lf better, record the new path as the correct peth in UsA: to gct 10 the node and propagate the corresponding change in LLo,st down through successor nodes as mcessary

One problem that may arise here is that cyeles may he introduced into the search graph. A Q.'cire is a path through. the graph. in which a given node appear.; more than onf.m. *For* example, the graph of Fig. 2.19 contains two cycleF. of length *two* One includes *the no deg (O*s in and (4+ 0): the other includes the nodes (0, 0) and (0. 3,n Whenever there is a cycliz, there can bo paths clr arbitrary length. Thus ii may become more difficult to how that a graph traversal zilgorithrli is guaranteed to tcrrninaie...

Treating the Fiarth proecss as a graph search rather than as a tree search reduces the amount of effort that is spent exploring essentially the NRITIC path scyerall times. But it mcwires additional et'Tort each time a node is generated tit see if it has beer; generated berure. 'Whether this effort is jusiilled depends on particular problem. If it k likely that the sanic node will be generated in several different ways, then it is more worthy:hire IR.) use a graph procedure than if 5Aich duplication will .happen only rarety.

Graph. searcli procedures *arc-* csixcially useful for dealim! with parzia1.11,.. crirnmurative production system in which a set uif operu.iions win produce the same re..4ilt regardles!... of the order in which the operations. are appTied, A systematic search procedure. v. ill try marry of the permutationLi of thi...se operators and so will generaie ihe K.aire node manyI i ii1 4, Tills is e.x.i.o..113-..1/41Lat harsivned i.11 w.iirier *jug ex.iimplif* shown atH.yve.

24 ADDITIONAL PROBLEMS

Sever41 pmblernK hnve been discus-ie4.1 ihR¯roighout this chapter. Other pi-t.thlerns have not yet been mention . hut itre common' throq.1·14.11.0 ihe. AI iiiirruture Some haihr kwuume....• classics Lint no AI book could be ⁴1:¹1PLYIPle¹leEti1.[it their!, SO Vve preseni in this section_ A u..eful exercise+ at this pint, 'would !¯w: to evitinint each uf them in liFht tile teriNitic..; we have 'jug discuseti_

A h•ic I j List i catior) is poy1.1i.ipi rqui red he rare this parade of toy problcms is pi esonied. Arti LcIlivcno..! is not nieftly a scion= of in problimis and rnicroworlds (uch EIS OW blocks world). or the [it h n ique thm ha' bccn vc Io ii for r hi,' so problems. have~ he t~ the con' Of sy_stc[ns ill a1 sotve very novo cv prib I ems. So think about these. problenis not a.2.: defining the scope of Al but rather as providing a core from which much. !nun: has deivelitped.

The Missionaries and Cannibals Problem.

Three and uhreL.i. codinihak find thelliNCI% OA (Irv,: side Of ha\ e agreed ih.ai they 'would all lidi; to get tEl iht.. other side. But the missiomirie..' iire riot Avail el e the cannihals have agreed to. Su the ivkarit mallag• the trip across the [Re' in Nadi alai The itunther nlissioliELEies aril eidicr side of the river is ricvor legs than the number of cannibals who am on the smile Hide_ The unly boat ayaii.able 11014.5 only two pcople at *a.* .f.ltwi can everfonc~i t across (ht. river without the missionarics. risking being 12aten?

The Tower *of 'fano'*

rnewiten2. near Hanoi !here k rionastery whos.1tti monk.Li. devule their •fves to a very In their imuri.....-,1111 are throe NAIL poms. On thu-se posts is a :1/40 cif si yo.y- four disks, each with a htgeiii the etnter L'Lnd tach of rt di Iry rem 11110M,LN1L:r)' Was ebtablisl Mai I. all or tie disio i.vae i 1 pi. ow of the punt w, each s.1 in. on the. one 'um larger that; it. The monks' last is lo move all of ale disks to one or the other pegs_ Only one diLA bc moved time. and all the other disks musi be. on Einc ir the Tri 41,ddi 'Mr!. tit no time during i he proi:ess. may a rli be. placed on top to a qrnaller diskr The third peg can. of ..:41111-4.4}, fsce,,I u. temponiry restinv place TUr thc disks. Whig is ([K eLiiiicke.st 141 the rt1 t ry w lc] accompliA their rriksion? Even 11112. best solution to [his problem will take ihe monks .1 i•er.. long time. This is fortunate. Ninee legend hay iI that E ht' wt'rid will end whirn ihey have

The fifonkey rrnd Bananas Pflablern

A hungry monkey Finds hirnscif in a 111f1111 in which a hunch or bananas is liansirig from thc ceiling.. The monkey. unfo 1.3 n tc ly, calm a t Rnhch the bananas. flowt v er, in 111c rimarn thcre arc u.lsc 1:a chair rind rr S rick_ The ceiling is ..jut the right height '›Li that a nionkot· itniling on a could knock the bananas down with the stick. The monkey *know L; how* to move around. carry other things around, reach lor the hanarns, and wave a stick in the air. 'What is I h tluenc of a.;tions for the monkey [c *take* to acquire. lunch?

SEND	DONALD	CROSS
+MORE	+GERALD	+R ADDS
MONTY	ROBERT	DANGER

Fig. 2.20 *Some CrypEartElvneiic Problems*

Cryptic nth *meth*

Consider an arithrrie[iC problem represented iii ?M em shuwn i if the examples in Fig. 2,20. Assign a decimal digit lo each. or the lettcrs in such a way that the answer to the problem is correct. If the same letter occurs more than once.. it must be assigned the same digit each time. No two different letters .ma)· be asi:iignt.:_.d tht! same digit.

Pe le &trategies for solving cryptarithritetic problems have been, studied intensively by Newell and Simon (.1972].

SUMMARY

this chapter. we have discussed the first two steps that must be taken toward the design of a program to soliye a particular problem!

1. Define the problem precisely. Specify the probleni space, the opemiors tor moving within the space, ;Ind the starting and goal statc(s).
2. Analyze the problem lo determine where it fall!. with respevi tu seven important issues,

The last two stcps for x...icieclopiris a program to solve that problem are. of course:

3, Identify and represen1 the knowledge required by (kiosk..
4. Choose one or more techniques for problem solving, and apply those techniques to the prob]cm.

Several gieneral-purposti ttehniques are presentedill the next chapter, and sevcral of them have already been ;alluded lo in the discussion (if the problem characieristics in this chapier. The relationships. between problem characieristic$awl .pecitic techniques should become even clearer as we go on. There, i n Pan II, we discuss. the issue of how domain knowledge is to be represented.

EXERCISES

. ln this chapter, ihe following problems were mentioned:

- Chess
- 8-puzzle
- ivlissionarieg. anK cannibals
- Monkey and bananas
- Water jug
- Traveling salesman
- Tuvli•r ref Hanoi
- Crypiarithrnetie

Analyze each of them with respect.to the seven. problem characteristics discussed in. Section 2.3.

2. Before we c:4111 Wive u pritiblem using state space sorch, we most define an appropriate state space_ For each of the pmblerns mentioned above for which it w ;1-; not done in the text. find a good state space representat Eon.
3. Describe how the branch-and-bourid technique email be used 10 find the shortest solution IL, a wafer Jug Problcul

4 . For each of the following types of problems. try to describe at food he function'.
(a) world
azi) Theorem prkwing..
(c) Missiorrarics. n d cannibals
5. !Give an example of . problem far which hreachill-tirst search would veni·1.: better thin depth-firm search_ Give an example of a prohlc n r ror which tic earch would work: boiler (ham breadth-ftrst search_
. Write an i4orilhorl to perform breadth-first :44:.-iarch of a problem xraph. Maki: sure your algorithm works properly MI hen a single node i generated a[more than one level in the graph.
7. Try to construct an .r4.'oritl¯im for solving blocks. world prob]rns., s¯uch the in in Fig- 2_10_ F ri nnt cheat by tool.....ing ahead Chapter 13,