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1 CMPS 3223 Theory of Computation Automata, Computability, & Complexity by Elaine Rich ~~~~~~ Slides provided by author Slides edited for use by MSU Department of Computer Science – R. Halverson 1 2 Why Study the Theory of Computation? Implementations come and go. Chapter 1 2 3 IBM 7090 Programming in the 1950's ENTRY SXA 4,RETURN LDQ X FMP A FAD B XCA FMP X FAD C STO RESULT RETURN TRA 0 A BSS 1 B BSS 1 C BSS 1 X BSS 1 TEMP BSS 1 STORE BSS 1 END Ax 2 + Bx +C 3 4 Programming in the 1970's IBM 360 JCL (Job Control Language) //MYJOB JOB (COMPRESS), 'VOLKER BANDKE',CLASS=P,COND=(0,NE) //BACKUP EXEC PGM=IEBCOPY //SYSPRINT DD SYSOUT=* //SYSUT1 DD DISP=SHR,DSN=MY.IMPORTNT.PDS //SYSUT2 DD DISP=(,CATLG), DSN=MY.IMPORTNT.PDS.BACKUP, // UNIT=3350,VOL=SER=DISK01, // DCB=MY.IMPORTNT.PDS, SPACE=(CYL,(10,10,20)) //COMPRESS EXEC PGM=IEBCOPY //SYSPRINT DD SYSOUT=* //MYPDS DD DISP=OLD,DSN=*.BACKUP.SYSUT1 //SYSIN DD * COPY INDD=MYPDS,OUTDD=MYPDS //DELETE2 EXEC PGM=IEFBR14 //BACKPDS DD DISP=(OLD,DELETE,DELETE), DSN=MY.IMPORTNT.PDS.BACKUP 4 5 Guruhood IBM's APL Language – Returns 1 if the largest value in a 3 element vector is greater than the sum of the other 2 and Returns 0 otherwise APL was very powerful for processing arrays & vectors 5 6 Why study this? Science of Computing Mathematical Properties (problems & algorithms) having nothing to do with current technology or languages E.G. Alan Turing – died 1954 Provides Abstract Structures Defines Provable Limits –Like "Big Oh" 6 7 Goals Study Principles of Problems themselves Does a solution exist? –If not, is there a restricted variation? Can solution be implemented in fixed memory? Is Solution efficient? –Growth of time & memory with problem size? Are there equivalent groups of problems? 7 8 Applications of the Theory Programming languages, compilers, & context-free grammars. –UTA FSMs (finite state machines) for parity checkers, vending machines, communication protocols, & building security devices. Interactive games as nondeterministic FSMs. Natural languages are mostly context-free. Speech understanding systems use probabilistic FSMs. Computational Biology: DNA & proteins are strings. The undecidability of a simple security model. Artificial Intelligence: the undecidability of first-order logic. 8 9 Languages and Strings This is one of MOST important chapters. It includes the TERMINOLOGY required to be successful in this course. KNOW this chapter & ALL DEFINITIONS!! Chapter 2 Slides provided by author Slides edited for use by MSU Department of Computer Science – R. Halverson 9 10 (1) Lexical analysis: Scan the program; break it into variable names, numbers, etc. (2) Parsing: Create a tree that corresponds to the sequence of operations to be executed, e.g., / + 10 2 5 (3) Optimization: Recognize, can skip first assignment since value is never used; can precompute the arithmetic expression, since it contains only constants. (4) Termination: Determine if program is guaranteed to halt. (5) Interpretation: Figure out what (if anything) useful program does. Let's Look at Some Problems int alpha, beta; alpha = 3; beta = (2 + 5) / 10; 10 11 Side Note: What is a Good Definition? A good definition consists of 2 components Category of term being defined Description of what distinguishes this particular element of the category from others 11 12 Definition Example Define automobile A mode of transportation – NO A vehicle with 4 wheels that allows a person to travel from on location to another – NO A mode of transportation by which I get to MSU – NO All the statements are true so Why Not? Which on is the best? Why? 12 13 Definition Example Define automobile A personal motorized vehicle with 4 wheels that allows a person to drive himself and others from on location to another –This is pretty good but does it completely distinguish an automobile from other similar vehicles? –What about a go cart? A pick-up truck? WHAT IT THE POINT OF THIS?? 13 14 A Framework for Analyzing Problems We need a single framework in which we can analyze a very diverse set of problems. The framework is Language Recognition *A language is a (possibly infinite) set of finite length strings over a finite alphabet. NOTE: Pay particular attention to use of finite & infinite in all definitions! 14 15 Alphabet - An alphabet is a non-empty, finite set of characters/symbols –Use to denote an alphabet Examples = { a, b } = { 0, 1, 2 } = { a, b, c,…z, A, B, … Z } = { #, $, *, @, & } 15 16 Strings A string is a finite sequence, possibly empty, of characters drawn from some alphabet . is the empty string * is the set of all possible strings over an alphabet . 16 17 Example Alphabets & Strings Alphabet nameAlphabet symbolsExample strings The lower case English alphabet { a, b, c, …, z } , aabbcg, aaaaa The binary alphabet { 0, 1 } , 0, 001100,11 A star alphabet{ ,, , , , } ,, A music alphabet { , , , , , , } , 17 18 Functions on Strings Length: |s| is the length of string s |s| is the number of characters in string s. | | = 0 | 1001101 | = 7 # c (s) is defined as the number of times that c occurs in s. # a (abbaaa) = 4. 18 19 More Functions on Strings Concatenation: the concatenation of 2 strings s and t is the string formed by appending t to s; written as s||t or more commonly, st Example: If x = good and y = bye, then xy = goodbye and yx = byegood Note that |xy| = |x| + |y| -- Is it always?? is the identity for concatenation of strings. So, s, t, w ((st)w = s(tw)) 19 20 More Functions on Strings Replication: For each string w and each natural number k, the string w k is: w 0 = w k+1 = w k w Examples: a 3 = aaa (bye) 2 = byebye a 0 b 3 = bbb b 2 y 2 e 2 = ?? Natural Numbers {0,1,2,…} 20 21 More Functions on Strings Reverse: For each string w, w R is defined as: if |w| = 0 then w R = w = if |w| = 1 then w R = w if |w| > 1 then: a (u * (w = ua)) So define w R = a u R OR if |w| > 1 then: a & u * w = ua So define w R = a u R Proof is by simple induction 21 22 Concatenation & Reverse of Strings Theorem: If w and x are strings, then (w x) R = x R w R. Example: (nametag) R = (tag) R (name) R = gateman In this course, will not use this too much! Not responsible for inductive proof on next slide. 22 23 Concatenation & Reverse of Strings Proof: By induction on |x|: |x| = 0: Then x = , and (wx) R = (w) R = (w) R = w R = R w R = x R w R. n 0 (((|x| = n) ((w x) R = x R w R)) ((|x| = n + 1) ((w x) R = x R w R))): Consider any string x, where |x| = n + 1. Then x = u a for some character a and |u| = n. So: (w x) R = (w (u a)) R rewrite x as ua = ((w u) a) R associativity of concatenation = a (w u) R definition of reversal = a (u R w R)induction hypothesis = (a u R) w R associativity of concatenation = (ua) R w R definition of reversal = x R w R rewrite ua as x 23 24 Relations on Strings - Substrings o Substring: string s is a substring of string t if s occurs contiguously in t o Every string is a substring of itself o is a substring of every string o Proper Substring: s is a proper substring of t iff s ≠ t o Suppose t = aabbcc. o Substrings: , a, aa, ab, bbcc, b, c, aabbcc o Proper substrings? o Others? 24 25 The Prefix Relations s is a prefix of t iff x * (t = xs). s is a proper prefix of t iff s is a prefix of t and s t. Examples: The prefixes of abba are: , a, ab, abb, abba. The proper prefixes of abba are: , a, ab, abb. Every string is a prefix of itself. is a suffix of every string. 25 26 The Suffix Relations s is a suffix of t iff x * (t = xs). s is a proper suffix of t iff s is a suffix of t and s t. Examples: The suffixes of abba are: , a, ba, bba, abba. The proper suffixes of abba are: , a, ba, bba. Every string is a suffix of itself. is a suffix of every string. 26 27 Defining a Language A language is a (finite or infinite) set of strings over a (finite) alphabet . Examples: Let = { a, b } Some languages over : = { } // the empty language, no strings { } // language contains only the empty string { a, b } { , a, aa, aaa, aaaa, aaaaa } 27 28 Defining a Language Two ways to define a language via a Machine = Automaton AKA – Computer Program Recognizer Generator Which do we want? Why? 28 29 ** * is defined as the set of all possible strings that can be formed from the alphabet * – * is a language * contains an infinite number of strings – * is countably infinite 29 30 * Example Let = { a, b } * = { , a, b,aa,ab,ba,bb,aaa,aab,… } Later, we will spend some more time studying *. 30 31 Defining Languages Remember we are defining a set Set Notation: L = { w * | description of w} L = { w {a,b,c}* | description of w} "description of w" can take many forms but must be precise Notation can vary, but must precisely define 31 32 Example Language Definitions L = {x { a, b }* | all a 's precede all b 's} aab,aaabb, and aabbb are in L. aba, ba, and abc are not in L. What about , a, aa, and bb ? L = {x : y { a, b }* | x = y a } Give an English description. 32 33 Example Language Definitions Let = { a, b } L = { w * : |w| < 5} L = { w * | # b (w) = 2} L = { w * | each a is followed by exactly 2 b's} L = { w * | w does not begin with a} 33 34 The Perils of Using English L = {x#y: x, y { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 }* and, when x & y are viewed as decimal representations of natural numbers, square(x) = y}. Examples: 3#9, 12#144 3#8, 12, 12#12#12 # 34 35 A Halting Problem Language L = {w | w is a C++ program that halts on all inputs} Well specified. Can we decide what strings it contains? Do we want a generator or recognizer? 35 36 More Examples What strings are in the following languages? L = {w { a, b }*: no prefix of w contains b } L = {w { a, b }*: no prefix of w starts with a } L = {w { a, b }*: every prefix of w starts with a } L = { a n : n 0} L = { ba 2 n : n 0} L = { b n a n : n 0} 36 37 Enumeration Enumeration: to list all strings in a language (set) Arbitrary order More useful: lexicographic order Shortest first Within a length, dictionary order Define linear order of arbitrary symbols 37 38 Lexicographic Enumeration {w { a, b }* : |w| is even} { , aa, ab, bb, aaaa, aaab, …} What string is next? How many strings of length 4? How many strings of length 6? 38 39 Cardinality of a Language Cardinality of a Language: the number of strings in the language | L | Smallest language over any is , with cardinality 0. The largest is *. Is this true? How big is it? Can a language be uncountable? 39 40 Countably Infinite Theorem: If then * is countably infinite. Proof: The elements of * can be lexicographically enumerated by the following procedure: Enumerate all strings of length 0, then length 1, then length 2, and so forth. Within the strings of a given length, enumerate them in dictionary order. This enumeration is infinite since there is no longest string in *. Since there exists an infinite enumeration of *, it is countably infinite. 40 41 How Many Languages Are There? Theorem: If then the set of languages over is uncountably infinite (uncountable). Proof: The set of languages defined on is P (*). * is countably infinite. By Theorem A.4, if S is a countably infinite set, P (S) is uncountably infinite. So P (*) is uncountably infinite. What does this mean?!?!?! 41 42 Functions on Languages Set (Language) functions Have the traditional meaning Union Intersection Complement Difference Language functions Concatenation Kleene star 42 43 Concatenation of Languages If L 1 and L 2 are languages over : L 1 L 2 = {w : s L 1 & t L 2 w = st } Examples: L 1 = { cat, dog } L 2 = { apple, pear } L 1 L 2 ={ catapple, catpear, dogapple, dogpear } L 2 L 1 ={ applecat,appledog,pearcat,peardog } 43 44 Concatenation of Languages { } is the identity for concatenation: L{ } = { }L = L is a zero for concatenation: L = L = 44 45 Concatenating Languages Defined Using Variables The scope of any variable used in an expression that invokes replication will be taken to be the entire expression. L 1 = { a n : n 0} L 2 = { b n : n 0} L 1 L 2 = { a n b m : n, m 0} L 1 L 2 { a n b n : n 0} 45 46 Kleene Star L* - language consisting of 0 or more concatenations of strings from L L* = { } {w * : w = w 1 w 2 … w k, k 1 & w 1, w 2, … w k L} Examples: L = { dog, cat, fish } L* = { , dog, cat, fish, dogdog, dogcat, dogfish,fishcatfish,fishdogdogfishcat, …} ~~~~~~~~~~~~ L 1 = a * L 2 = b * What is a*? b*? L 1 L 2 = L 2 L 1 = L 1 L 1 = 46 * 47 The Operator L + = language consisting of 1 or more concatenations of strings from L L + = L L* L + = L* - { } iff L Explain this definition!! When is L + ? 47 + 48 Closure A set S is closed under the operation @ if for every element x & y in S, x@y is also an element of S A set S is closed under the operation @ if for every element x S & y S, x@y S Examples 48 49 Semantics: Assigning Meaning to Strings When is the meaning of a string important? A semantic interpretation function assigns meanings to the strings of a language. Can be very complex. Example from English: I brogelled the yourtish. He's all thumbs. 49 50 Uniqueness??? Chocolate, please. I'd like chocolate. I'll have chocolate today. I guess I'll have chocolate. They all have the same meaning! 50 51 Uniqueness??? Hand Give me a hand. I smashed my hand in the door. Please hand me that book. These all have different meanings!!! 51 52 Uniqueness in CS??? int x = 4; x++; int x = 4; ++x; int x = 4; x = x + 1; int x = 4; x=x - -1; int x = 5; These all have the same result/meaning! 52 53 Semantic Interpretation Functions For formal languages: Programming languages Network protocol languages Database query languages HTML BNF For other kinds of "natural" languages: DNA Other computing Genetic algorithm solutions Other problem solutions 53 54 Chapter 2 Critical for success in this class!!! Homework Exercises –Page 19: 1-8, 8 provide example not proof Will be several quizzes over homework and lecture!! HW to hand in: –3, 6b, 7b, 8d, 8k –7 & 8 explain 54

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