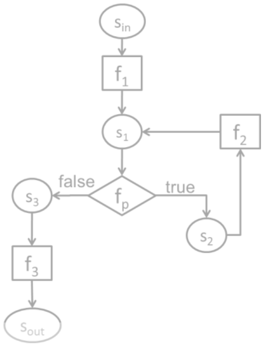
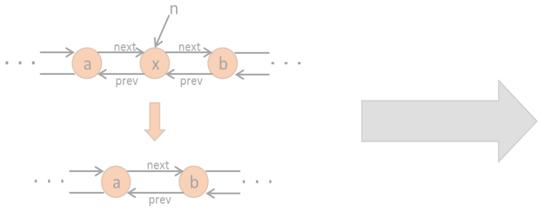
$$\exists c \forall in\ Q(c, in)$$

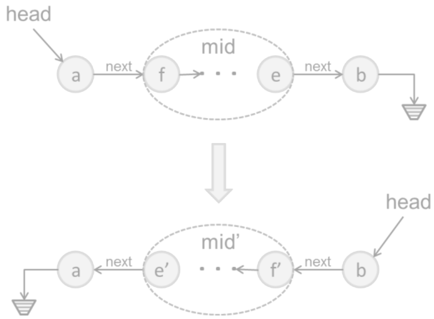
```
/* Average of x and y without using x+y (avoid overflow)*/
int avg(int x, int y){
  int t = expr({x/2, y/2, x%2, y%2, 2 }, {PLUS, DIV});
  assert t == (x+y)/2;
  return t;
}
```

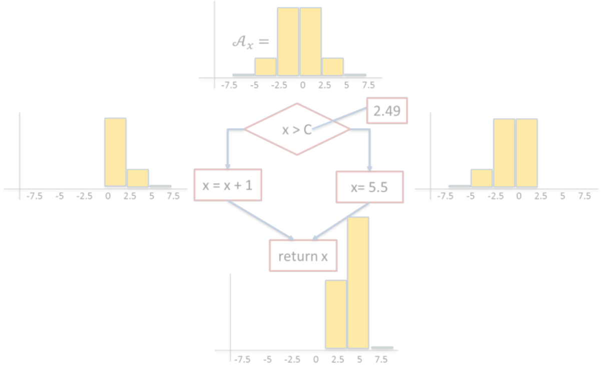




```
{
  s  = n.succ;
  p = n.pred;
  p.succ = s;
  s.pred = p;
}
```

Program Synthesis



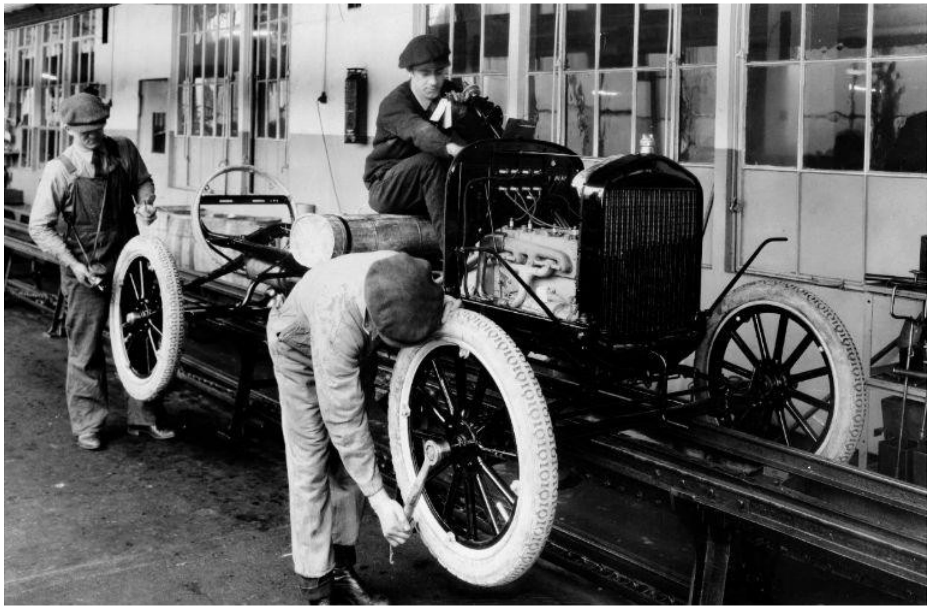


$$\varphi(p)$$

$$Sk[c](in)$$

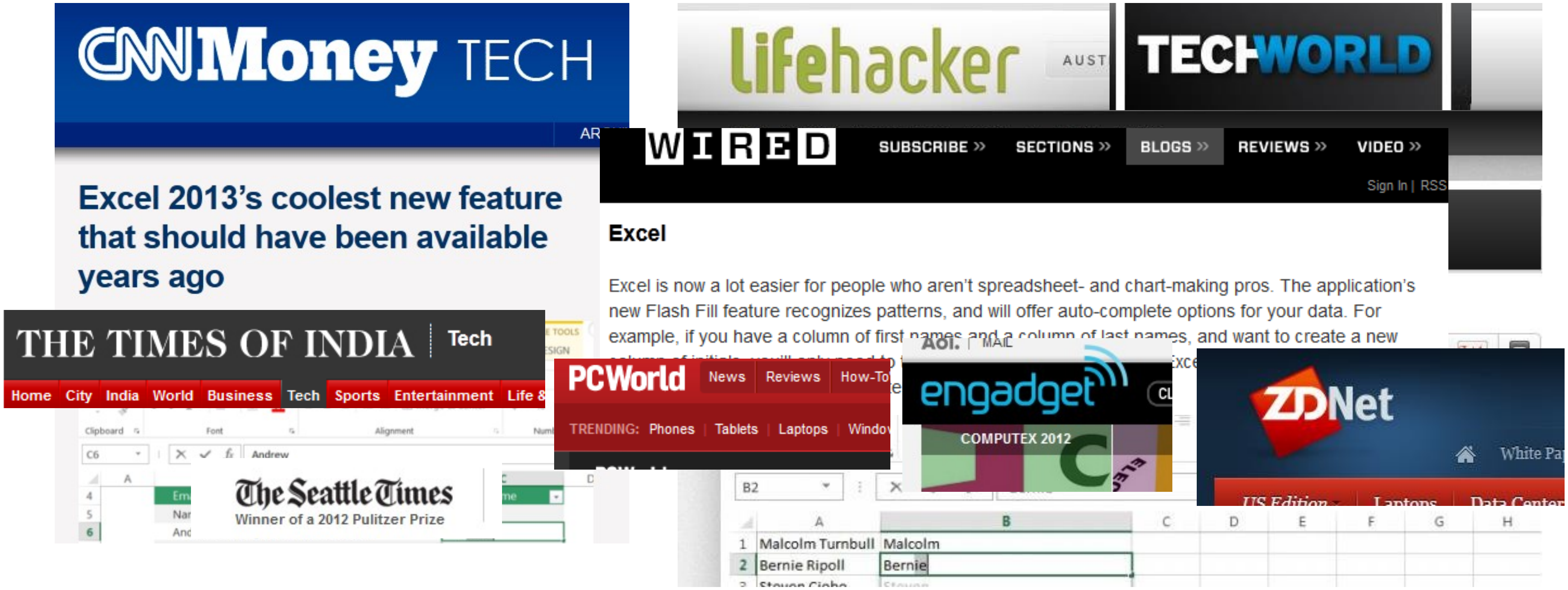
Introduction to Synthesis

The goal: automate programming



Modern program synthesis: FlashFill

[Gulwani 2011]



Excel 2013's coolest new feature that should have been available years ago

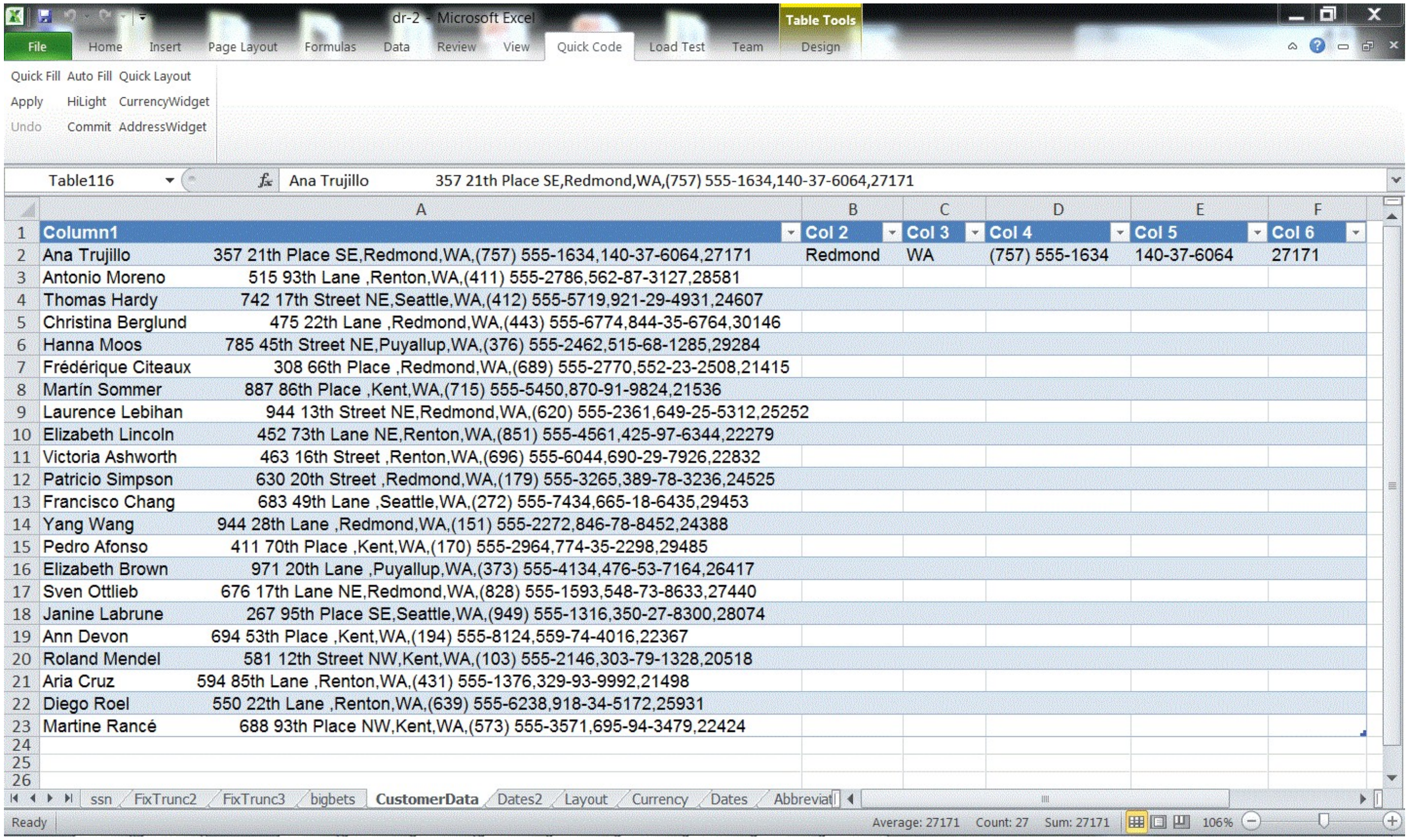
Excel

Excel is now a lot easier for people who aren't spreadsheet- and chart-making pros. The application's new Flash Fill feature recognizes patterns, and will offer auto-complete options for your data. For example, if you have a column of first names and a column of last names, and want to create a new

	A	B
1	Malcolm Turnbull	Malcolm
2	Bernie Ripoll	Bernie

FlashFill: a feature of Excel 2013

[Gulwani 2011]



Ana Trujillo 357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171

	A	B	C	D	E	F
1	Column1	Col 2	Col 3	Col 4	Col 5	Col 6
2	Ana Trujillo 357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171	Redmond	WA	(757) 555-1634	140-37-6064	27171
3	Antonio Moreno 515 93th Lane ,Renton,WA,(411) 555-2786,562-87-3127,28581					
4	Thomas Hardy 742 17th Street NE,Seattle,WA,(412) 555-5719,921-29-4931,24607					
5	Christina Berglund 475 22th Lane ,Redmond,WA,(443) 555-6774,844-35-6764,30146					
6	Hanna Moos 785 45th Street NE,Puyallup,WA,(376) 555-2462,515-68-1285,29284					
7	Frédérique Citeaux 308 66th Place ,Redmond,WA,(689) 555-2770,552-23-2508,21415					
8	Martín Sommer 887 86th Place ,Kent,WA,(715) 555-5450,870-91-9824,21536					
9	Laurence Lebihan 944 13th Street NE,Redmond,WA,(620) 555-2361,649-25-5312,25252					
10	Elizabeth Lincoln 452 73th Lane NE,Renton,WA,(851) 555-4561,425-97-6344,22279					
11	Victoria Ashworth 463 16th Street ,Renton,WA,(696) 555-6044,690-29-7926,22832					
12	Patricio Simpson 630 20th Street ,Redmond,WA,(179) 555-3265,389-78-3236,24525					
13	Francisco Chang 683 49th Lane ,Seattle,WA,(272) 555-7434,665-18-6435,29453					
14	Yang Wang 944 28th Lane ,Redmond,WA,(151) 555-2272,846-78-8452,24388					
15	Pedro Afonso 411 70th Place ,Kent,WA,(170) 555-2964,774-35-2298,29485					
16	Elizabeth Brown 971 20th Lane ,Puyallup,WA,(373) 555-4134,476-53-7164,26417					
17	Sven Ottlieb 676 17th Lane NE,Redmond,WA,(828) 555-1593,548-73-8633,27440					
18	Janine Labrune 267 95th Place SE,Seattle,WA,(949) 555-1316,350-27-8300,28074					
19	Ann Devon 694 53th Place ,Kent,WA,(194) 555-8124,559-74-4016,22367					
20	Roland Mendel 581 12th Street NW,Kent,WA,(103) 555-2146,303-79-1328,20518					
21	Aria Cruz 594 85th Lane ,Renton,WA,(431) 555-1376,329-93-9992,21498					
22	Diego Roel 550 22th Lane ,Renton,WA,(639) 555-6238,918-34-5172,25931					
23	Martine Rancé 688 93th Place NW,Kent,WA,(573) 555-3571,695-94-3479,22424					
24						
25						
26						

FlashFill: a feature of Excel 2013

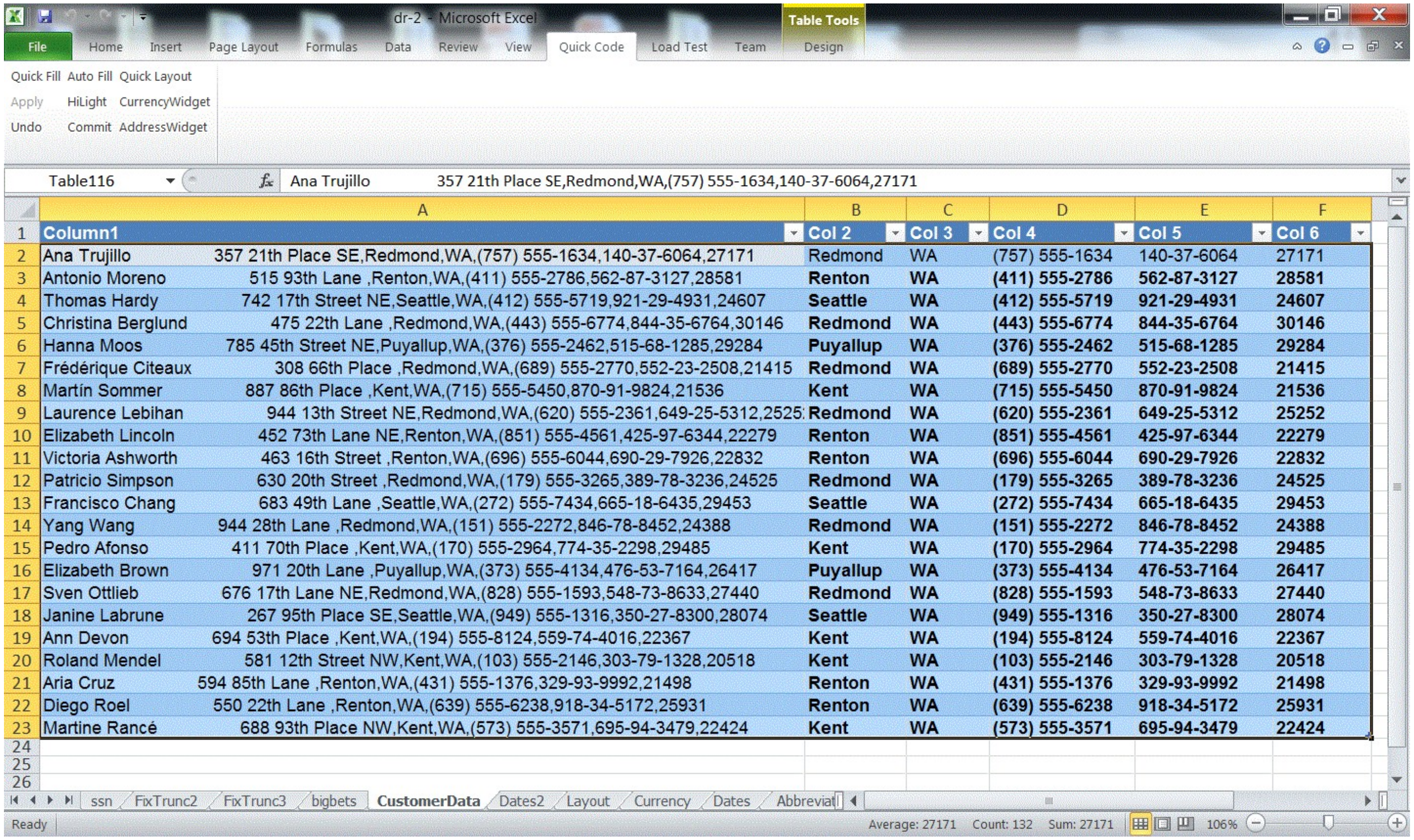


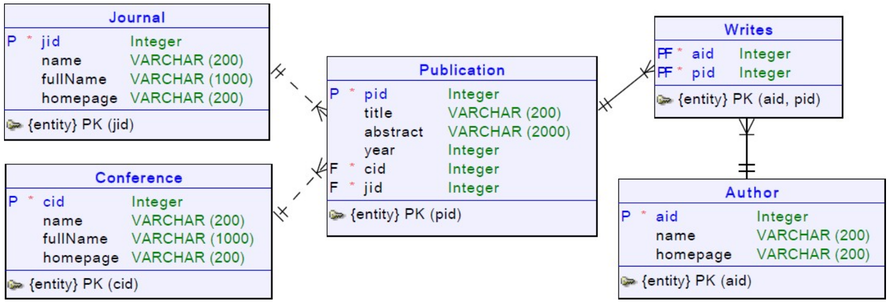
Table116 | Ana Trujillo 357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171

	A	B	C	D	E	F
1	Column1	Col 2	Col 3	Col 4	Col 5	Col 6
2	Ana Trujillo 357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171	Redmond	WA	(757) 555-1634	140-37-6064	27171
3	Antonio Moreno 515 93th Lane ,Renton,WA,(411) 555-2786,562-87-3127,28581	Renton	WA	(411) 555-2786	562-87-3127	28581
4	Thomas Hardy 742 17th Street NE,Seattle,WA,(412) 555-5719,921-29-4931,24607	Seattle	WA	(412) 555-5719	921-29-4931	24607
5	Christina Berglund 475 22th Lane ,Redmond,WA,(443) 555-6774,844-35-6764,30146	Redmond	WA	(443) 555-6774	844-35-6764	30146
6	Hanna Moos 785 45th Street NE,Puyallup,WA,(376) 555-2462,515-68-1285,29284	Puyallup	WA	(376) 555-2462	515-68-1285	29284
7	Frédérique Citeaux 308 66th Place ,Redmond,WA,(689) 555-2770,552-23-2508,21415	Redmond	WA	(689) 555-2770	552-23-2508	21415
8	Martín Sommer 887 86th Place ,Kent,WA,(715) 555-5450,870-91-9824,21536	Kent	WA	(715) 555-5450	870-91-9824	21536
9	Laurence Lebihan 944 13th Street NE,Redmond,WA,(620) 555-2361,649-25-5312,2525	Redmond	WA	(620) 555-2361	649-25-5312	25252
10	Elizabeth Lincoln 452 73th Lane NE,Renton,WA,(851) 555-4561,425-97-6344,22279	Renton	WA	(851) 555-4561	425-97-6344	22279
11	Victoria Ashworth 463 16th Street ,Renton,WA,(696) 555-6044,690-29-7926,22832	Renton	WA	(696) 555-6044	690-29-7926	22832
12	Patricio Simpson 630 20th Street ,Redmond,WA,(179) 555-3265,389-78-3236,24525	Redmond	WA	(179) 555-3265	389-78-3236	24525
13	Francisco Chang 683 49th Lane ,Seattle,WA,(272) 555-7434,665-18-6435,29453	Seattle	WA	(272) 555-7434	665-18-6435	29453
14	Yang Wang 944 28th Lane ,Redmond,WA,(151) 555-2272,846-78-8452,24388	Redmond	WA	(151) 555-2272	846-78-8452	24388
15	Pedro Afonso 411 70th Place ,Kent,WA,(170) 555-2964,774-35-2298,29485	Kent	WA	(170) 555-2964	774-35-2298	29485
16	Elizabeth Brown 971 20th Lane ,Puyallup,WA,(373) 555-4134,476-53-7164,26417	Puyallup	WA	(373) 555-4134	476-53-7164	26417
17	Sven Ottlieb 676 17th Lane NE,Redmond,WA,(828) 555-1593,548-73-8633,27440	Redmond	WA	(828) 555-1593	548-73-8633	27440
18	Janine Labrune 267 95th Place SE,Seattle,WA,(949) 555-1316,350-27-8300,28074	Seattle	WA	(949) 555-1316	350-27-8300	28074
19	Ann Devon 694 53th Place ,Kent,WA,(194) 555-8124,559-74-4016,22367	Kent	WA	(194) 555-8124	559-74-4016	22367
20	Roland Mendel 581 12th Street NW,Kent,WA,(103) 555-2146,303-79-1328,20518	Kent	WA	(103) 555-2146	303-79-1328	20518
21	Aria Cruz 594 85th Lane ,Renton,WA,(431) 555-1376,329-93-9992,21498	Renton	WA	(431) 555-1376	329-93-9992	21498
22	Diego Roel 550 22th Lane ,Renton,WA,(639) 555-6238,918-34-5172,25931	Renton	WA	(639) 555-6238	918-34-5172	25931
23	Martine Rancé 688 93th Place NW,Kent,WA,(573) 555-3571,695-94-3479,22424	Kent	WA	(573) 555-3571	695-94-3479	22424
24						
25						
26						

Modern program synthesis: SQLizer

[Yaghmazadeh et al. 2017]

Problem: “Find the number of papers in OOPSLA 2010”



		Journal	
P	*	jid	Integer
		name	VARCHAR (200)
		fullName	VARCHAR (1000)
		homepage	VARCHAR (200)
		{entity} PK (jid)	

		Conference	
P	*	cid	Integer
		name	VARCHAR (200)
		fullName	VARCHAR (1000)
		homepage	VARCHAR (200)
		{entity} PK (cid)	

		Publication	
P	*	pid	Integer
		title	VARCHAR (200)
		abstract	VARCHAR (2000)
		year	Integer
F	*	cid	Integer
F	*	jid	Integer
		{entity} PK (pid)	

		Writes	
PF	*	aid	Integer
PF	*	pid	Integer
		{entity} PK (aid, pid)	

		Author	
P	*	aid	Integer
		name	VARCHAR (200)
		homepage	VARCHAR (200)
		{entity} PK (aid)	

Output:

```
SELECT count(Publication.pid)
FROM Publication JOIN Conference ON Publication.cid = Conference.cid
WHERE Conference.name = "OOPSLA" AND Publication.year = 2010
```

Modern program synthesis: Sketch

[Solar-Lezama 2013]

Problem: isolate the least significant zero bit in a word

- example: 0010 0101 → 0000 0010

Easy to implement with a loop

```
int W = 32;

bit[W] isolate0 (bit[W] x) {      // W: word size
       bit[W] ret = 0;
       for (int i = 0; i < W; i++)
              if (!x[i]) { ret[i] = 1; return ret; }
}
```

Can this be done more efficiently with bit manipulation?

- Trick: adding 1 to a string of ones turns the next zero to a 1
- i.e. 000111 + 1 = 001000

Sketch: space of possible implementations

```
/**
 * Generate the set of all bit-vector expressions
 * involving +, &, xor and bitwise negation (~).
*/

generator bit[W] gen(bit[W] x){
    if(??) return x;
    if(??) return ??;
    if(??) return ~gen(x);
    if(??){
        return {| gen(x) (+ | & | ^) gen(x) |};
    }
}
```

Sketch: synthesis goal

```
generator bit[W] gen(bit[W] x, int depth){
    assert depth > 0;
    if(??) return x;
    if(??) return ??;
    if(??) return ~gen(x, depth-1);
    if(??){
        return {| gen(x, depth-1) (+ | & | ^) gen(x, depth-1) |};
    }
}

bit[W] isolate0fast (bit[W] x) implements isolate0 {
     return gen(x, 3);
}
```

Sketch: output

```
bit[W] isolate0fast (bit[W] x) {
  return (~x) & (x + 1);
}
```

Modern program synthesis: Synquid

[Polikarpova et al. 2016]

Problem: intersection of strictly sorted lists

- example: intersect [4, 8, 15, 16, 23, 42] [8, 16, 32, 64] → [8, 16]

Also: we want a guarantee that it’s correct on all inputs!

Synquid: synthesis goal and components

Step 1: define synthesis goal as a *type*

sorted list

```
intersect :: xs:SList a  →   ys:SList a →
                       {ν:SList a | elems ν = elems xs ∩
                                              elems ys}
```

the set of elements

Step 2: define a set of components

- Which primitive operations is our function likely to use?
- Here: {`Nil`, `Cons`, `<`}

Synquid: synthesis goal and components

Example: Synquid

specification

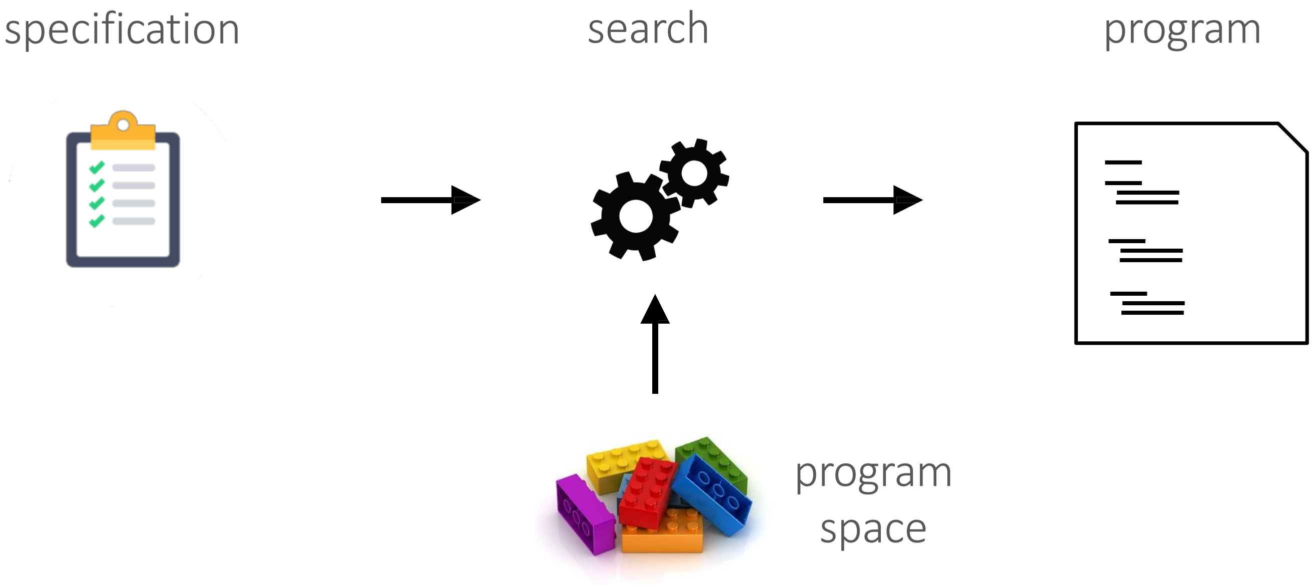
```
intersect :: xs:SList a  →
  ys:SList a  →
  {ν:SList a | elems ν = elems xs ∩
                         elems ys}
```

→

program

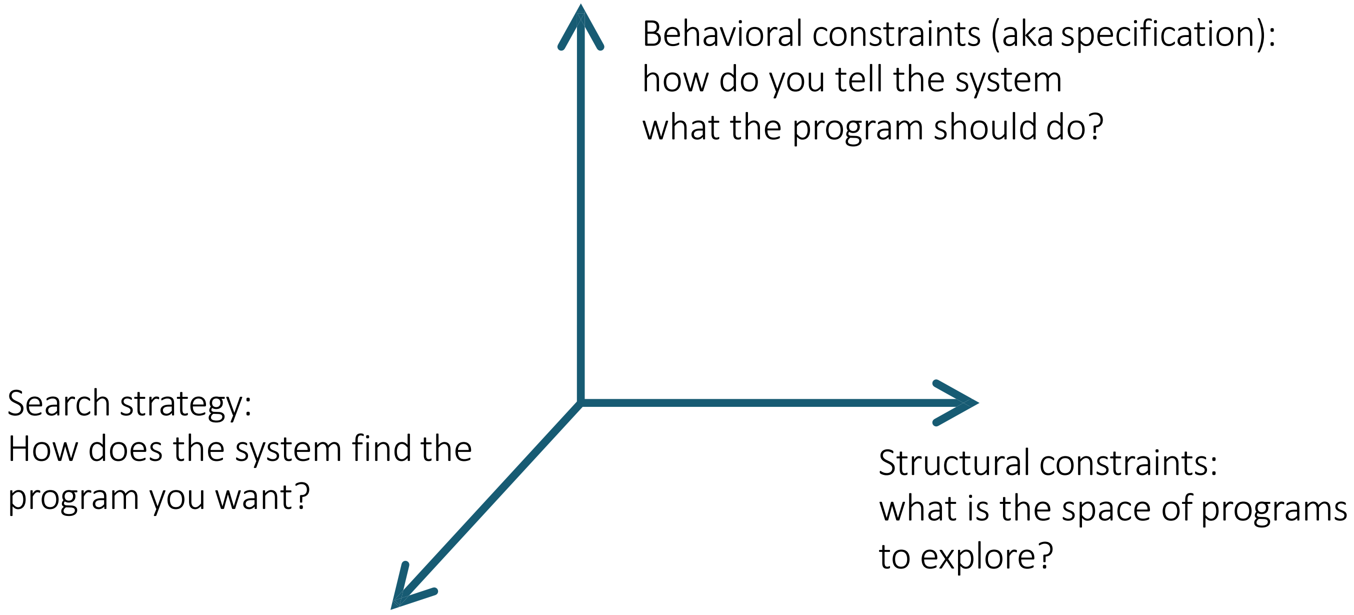
```
intersection = \xs . \ys .
  match xs with
    Nil -> xs
    Cons x xt ->
      match ys with
        Nil -> ys
        Cons y yt ->
          if x < y
          then intersection xt ys
          else
            if y < x
            then intersection xs yt
            else Cons x (intersection xt yt)
```

What is program synthesis?



Dimensions in program synthesis

[Gulwani 2010]



Behavioral constraints (aka specification):
how do you tell the system
what the program should do?

Search strategy:
How does the system find the
program you want?

Structural constraints:
what is the space of programs
to explore?