An Application of Ramsey's Theorem to Proving Programs Terminate: An Exposition

William Gasarch-U of MD

Who is Who

1. Work by
   1.1 Floyd,
   1.2 Byron Cook, Andreas Podelski, Andrey Rybalchenko,
   1.3 Lee, Jones, Ben-Amram
   1.4 Others
2. Pre-Apology: Not my area-some things may be wrong.
3. Pre-Brag: Not my area-some things may be understandable.

Problem: Given a program we want to prove it terminates no matter what user does (called TERM problem).

1. Impossible in general- Harder than Halting.
2. But can do this on some simple progs. (We will.)

Overview II

In this talk I will:

1. Do example of traditional method to prove progs terminate.
2. Do harder example of traditional method.
3. DIGRESSION: A very short lecture on Ramsey Theory.
4. Do that same harder example using Ramsey Theory.
5. Compelling example with Ramsey Theory.
6. Do same example with Ramsey Theory and Matrices.

Notation

1. Will use psuedo-code progs.
2. KEY: If A is a set then the command

   ```
   x = input(A)
   ```

   means that x gets some value from A that the user decides.
3. Note: we will want to show that no matter what the user does the program will halt.
4. The code

   ```
   (x,y) = (f(x,y),g(x,y))
   ```

   means that simultaneously x gets f(x,y) and y gets g(x,y).

Easy Example of Traditional Method

```
(x,y,z) = (input(INT), input(INT), input(INT))
While x>0 and y>0 and z>0
        control = input(1,2,3)
        if control == 1 then
                (x,y,z)=(x+1,y-1,z-1)
        else
        if control == 2 then
                (x,y,z)=(x-1,y+1,z-1)
        else
                (x,y,z)=(x-1,y-1,z+1)
```

Sketch of Proof of termination:

Easy Example of Traditional Method

```
(x,y,z) = (input(INT), input(INT), input(INT))
While x>0 and y>0 and z>0
        control = input(1,2,3)
        if control == 1 then
                (x,y,z)=(x+1,y-1,z-1)
        else
        if control == 2 then
                (x,y,z)=(x-1,y+1,z-1)
        else
                (x,y,z)=(x-1,y-1,z+1)
```

Sketch of Proof of termination:
Whatever the user does x+y+z is decreasing.

Easy Example of Traditional Method

```
(x,y,z) = (input(INT), input(INT), input(INT))
While x>0 and y>0 and z>0
        control = input(1,2,3)
        if control == 1 then
                (x,y,z)=(x+1,y-1,z-1)
        else
        if control == 2 then
                (x,y,z)=(x-1,y+1,z-1)
        else
                (x,y,z)=(x-1,y-1,z+1)
```

Sketch of Proof of termination:
Whatever the user does x+y+z is decreasing.
Eventually x+y+z=0 so prog terminates there or earlier.

What is Traditional Method?

General method due to Floyd: Find a function f(x,y,z) from the values of the variables to N such that

1. in every iteration f(x,y,z) decreases
2. if f(x,y,z) is every 0 then the program must have halted.

Note: Method is more general- can map to a well founded order such that in every iteration f(x,y,z) decreases in that order, and if f(x,y,z) is ever a min element then program must have halted.

Hard Example of Traditional Method

```
(x,y,z) = (input(INT),input(INT),input(INT))
While x>0 and y>0 and z>0
        control = input(1,2)
        if control == 1 then
                (x,y) =(x-1,input(y+1,y+2,...))
        else
                (y,z)=(y-1,input(z+1,z+2,...))
```

Sketch of Proof of termination:

Hard Example of Traditional Method

```
(x,y,z) = (input(INT),input(INT),input(INT))
While x>0 and y>0 and z>0
        control = input(1,2)
        if control == 1 then
                (x,y) =(x-1,input(y+1,y+2,...))
        else
                (y,z)=(y-1,input(z+1,z+2,...))
```

Sketch of Proof of termination:
Use Lex Order: $(0,0,0) < (0,0,1) < \cdots < (0,1,0) \cdots$.
Note: $(4, 10^{100}, 10^{10!}) < (5,0,0)$.

Hard Example of Traditional Method

```
(x,y,z) = (input(INT),input(INT),input(INT))
While x>0 and y>0 and z>0
        control = input(1,2)
        if control == 1 then
                (x,y) =(x-1,input(y+1,y+2,...))
        else
                (y,z)=(y-1,input(z+1,z+2,...))
```

Sketch of Proof of termination:
Use Lex Order: $(0,0,0) < (0,0,1) < \cdots < (0,1,0) \cdots$.
Note: $(4, 10^{100}, 10^{10!}) < (5,0,0)$.
In every iteration (x,y,z) decreases in this ordering.

Hard Example of Traditional Method

```
(x,y,z) = (input(INT),input(INT),input(INT))
While x>0 and y>0 and z>0
        control = input(1,2)
        if control == 1 then
                (x,y) =(x-1,input(y+1,y+2,...))
        else
                (y,z)=(y-1,input(z+1,z+2,...))
```

Sketch of Proof of termination:
Use Lex Order: $(0,0,0) < (0,0,1) < \cdots < (0,1,0) \cdots$.
Note: $(4, 10^{100}, 10^{10!}) < (5,0,0)$.
In every iteration (x,y,z) decreases in this ordering.
If hits bottom then all vars are 0 so must halt then or earlier.

Notes about Proof

1. Bad News: We had to use a funky ordering. This might be hard for a proof checker to find. (Funky is not a formal term.)
2. Good News: We only had to reason about what happens in one iteration.

Keep these in mind- our later proof will use a nice ordering but will need to reason about a block of instructions.

Digression Into Ramsey Theory (Parties!)

The following are known:

1. If you have 6 people at a party then either 3 of them mutually know each other or 3 of them mutually don't know each other.

Digression Into Ramsey Theory (Parties!)

The following are known:

1. If you have 6 people at a party then either 3 of them mutually know each other or 3 of them mutually don't know each other.
2. If you have 18 people at a party then either 4 of them mutually know each other or 4 of them mutually do not know each other.

Digression Into Ramsey Theory (Parties!)

The following are known:

1. If you have 6 people at a party then either 3 of them mutually know each other or 3 of them mutually don't know each other.
2. If you have 18 people at a party then either 4 of them mutually know each other or 4 of them mutually do not know each other.
3. If you have 2^{2k-1} people at a party then either k of them mutually know each other of k of them mutually do not know each other.

Digression Into Ramsey Theory (Parties!)

The following are known:

1. If you have 6 people at a party then either 3 of them mutually know each other or 3 of them mutually don't know each other.
2. If you have 18 people at a party then either 4 of them mutually know each other or 4 of them mutually do not know each other.
3. If you have 2^{2k-1} people at a party then either k of them mutually know each other of k of them mutually do not know each other.
4. If you have an infinite number of people at a party then either there exists an infinite subset that all know each other or an infinite subset that all do not know each other.

Digression Into Ramsey Theory (Math!)

Definition

Let $c, k, n \in \mathrm{N}$. K_n is the complete graph on n vertices (all pairs are edges). K_ω is the infinite complete graph. A c-coloring of K_n is a c-coloring of the edges of K_n. A homogeneous set is a subset H of the vertices such that every pair has the same color (e.g., 10 people all of whom know each other).

The following are known.

Definition

Let $c, k, n \in \mathrm{N}$. K_n is the complete graph on n vertices (all pairs are edges). K_ω is the infinite complete graph. A c-coloring of K_n is a c-coloring of the edges of K_n. A homogeneous set is a subset H of the vertices such that every pair has the same color (e.g., 10 people all of whom know each other).

The following are known.

1. For all 2-colorings of K_6 there is a homog 3-set.

Digression Into Ramsey Theory (Math!)

Definition

Let $c, k, n \in \mathrm{N}$. K_n is the complete graph on n vertices (all pairs are edges). K_ω is the infinite complete graph. A c-coloring of K_n is a c-coloring of the edges of K_n. A homogeneous set is a subset H of the vertices such that every pair has the same color (e.g., 10 people all of whom know each other).

The following are known.

1. For all 2-colorings of K_6 there is a homog 3-set.
2. For all c-colorings of $K_{c^{ck-c}}$ there is a homog k-set.

Digression Into Ramsey Theory (Math!)

Definition

Let $c, k, n \in \mathrm{N}$. K_n is the complete graph on n vertices (all pairs are edges). K_ω is the infinite complete graph. A c-coloring of K_n is a c-coloring of the edges of K_n. A homogeneous set is a subset H of the vertices such that every pair has the same color (e.g., 10 people all of whom know each other).

The following are known.

1. For all 2-colorings of K_6 there is a homog 3-set.
2. For all c-colorings of $K_{c^{ck-c}}$ there is a homog k-set.
3. For all c-colorings of the K_ω there exists a homog ω-set.

Alt Proof Using Ramsey

```
(x,y,z) = (input(INT),input(INT),input(INT))
While x>0 and y>0 and z>0
        control = input(1,2)
        if control == 1 then
                (x,y) =(x-1,input(y+1,y+2,...))
        else
                (y,z)=(y-1,input(z+1,z+2,...))
```

Begin Proof of termination:

```
(x,y,z) = (input(INT),input(INT),input(INT))
While x>0 and y>0 and z>0
        control = input(1,2)
        if control == 1 then
                (x,y) =(x-1,input(y+1,y+2,...))
        else
                (y,z)=(y-1,input(z+1,z+2,...))
```

Begin Proof of termination:
If program does not halt then there is infinite sequence $(x_1, y_1, z_1), (x_2, y_2, z_2), \ldots,$ representing state of vars.

Reasoning about Blocks

```
control = input(1,2)
if control == 1 then
        (x,y) =(x-1,input(y+1,y+2,...))
else
        (y,z)=(y-1,input(z+1,z+2,...))
```

Reasoning about Blocks

```
control = input(1,2)
if control == 1 then
          (x,y) =(x-1,input(y+1,y+2,...))
else
          (y,z)=(y-1,input(z+1,z+2,...))
```

Look at $(\mathrm{x}_i, \mathrm{y}_i, \mathrm{z}_i), \ldots, (\mathrm{x}_j, \mathrm{y}_j, \mathrm{z}_j)$.

1. If control is ever 1 then $\mathrm{x}_i > \mathrm{x}_j$.
2. If control is never 1 then $\mathrm{y}_i > \mathrm{y}_j$.

```
control = input(1,2)
if control == 1 then
        (x,y) =(x-1,input(y+1,y+2,...))
else
        (y,z)=(y-1,input(z+1,z+2,...))
```

Look at $(x_i, y_i, z_i), \ldots, (x_j, y_j, z_j)$.

1. If control is ever 1 then $x_i > x_j$.
2. If control is never 1 then $y_i > y_j$.

Upshot: For all $i < j$ either $x_i > x_j$ or $y_i > y_j$.

Use Ramsey

If program does not halt then there is infinite sequence $(\mathrm{x}_1, \mathrm{y}_1, \mathrm{z}_1), (\mathrm{x}_2, \mathrm{y}_2, \mathrm{z}_2), \ldots,$ representing state of vars.
For all $i < j$ either $\mathrm{x}_i > \mathrm{x}_j$ or $\mathrm{y}_i > \mathrm{y}_j$.
Define a 2-coloring of the edges of K_ω:

$$COL(i,j) = \begin{cases} X \text{ if } \mathrm{x}_i > \mathrm{x}_j \\ Y \text{ if } \mathrm{y}_i > \mathrm{y}_j \end{cases} \tag{1}$$

By Ramsey there exists homog set $i_1 < i_2 < i_3 < \cdots$.
If color is X then $\mathrm{x}_{i_1} > \mathrm{x}_{i_2} > \mathrm{x}_{i_3} > \cdots$
If color is Y then $\mathrm{y}_{i_1} > \mathrm{y}_{i_2} > \mathrm{y}_{i_3} > \cdots$
In either case will have eventually have a var ≤ 0 and hence program must terminate. Contradiction.

Compare and Contrast

1. Trad. proof used lex order on N^3–complicated!
2. Ramsey Proof used only used the ordering N.
3. Traditional proof only had to reason about single steps.
4. Ramsey Proof had to reason about blocks of steps.

What do YOU think?

VOTE:

1. Traditional Proof!
2. Ramsey Proof!
3. Stewart/Colbert in 2012!

A More Compelling Example

```
(x,y) = (input(INT),input(INT))
While x>0 and y>0
       control = input(1,2)
       if control == 1 then
              (x,y)=(x-1,x)
       else
       if control == 2 then
              (x,y)=(y-2,x+1)
```

Reasoning about Blocks

If program does not halt then there is infinite sequence $(x_1, y_1), (x_2, y_2), \ldots,$ representing state of vars. Need to show that in any if $i < j$ then either $x_i > x_j$ or $y_i > y_j$. Can show that one of the following must occur:

1. $x_j < x_i$ and $y_j \le x_i$ (x decs),
2. $x_j < y_i - 1$ and $y_j \le x_i + 1$ (x+y decs so one of x or y decs),
3. $x_j < y_i - 1$ and $y_j < y_i$ (y decs),
4. $x_j < x_i$ and $y_j < y_i$ (x and y both decs).

Now use Ramsey argument.

Comments

1. The condition in the last proof is called a Termination Invariant. They are used to strengthened the induction hypothesis.
2. The proof was found by the system of B. Cook et al.
3. Looking for a Termination Invariant is the hard part to automate but they have automated it.
4. Can we use these techniques to solve a fragment of Term Problem?

Model control=1 via a Matrix

```
if control == 1 then (x,y)=(x-1,x)
```

Model as a matrix A indexed by x,y,x+y.

$$\begin{pmatrix} -1 & 0 & 1 \\ \infty & \infty & \infty \\ \infty & \infty & \infty \end{pmatrix}$$

Entry (x,y) is difference between OLD x and NEW y.
Entry (x,x) is most interesting- if neg then x decreased.

Model control=2 via a Matrix

```
if control == 2 then (x,y)=(y-2,x+1)
```

Model as a matrix B indexed by x,y,x+y.

$$\begin{pmatrix} \infty & 1 & \infty \\ -2 & \infty & \infty \\ \infty & \infty & -1 \end{pmatrix}$$

Redefine Matrix Mult

A and B matrices, C=AB defined by

$$c_{ij} = \min_k \{a_{ik} + b_{kj}\}.$$

Lemma

If matrix A models a statement s_1 and matrix B models a statement s_2 then matrix AB models what happens if you run $s_1; s_2$.

Matrix Proof that Program Terminates

- A is matrix for control=1. B is matrix for control=2.
- Show: any prod of A's and B's some diag is negative.
- Hence in any finite seg one of the vars decreases.
- Hence, by Ramsey proof, the program always terminates

General Program

```
X = (input(INT),...,input(INT)
While x[1]>0 and x[2]>0 and ... x[n]>0
 control = input(1,2,3,...,m)
 if control==1
    X = F1(X,input(INT,...,input(INT))
  else
  if control==2
    X = F2(X,input(INT),...,input(INT))
  else...
  else
  if control==m
    X = Fm(X,input(INT),...,input(INT))
```

Fragment of TERM decidable?

Definition

The TERMINATION PROBLEM: Given $F_1, \ldots, F_m$ can we determine if the following holds:

For all ω-seq of inputs the program halts

1. This is HARDER than HALT. This is Σ^1_1-complete.
2. EASY to show is HARD: use polynomials and Hilbert's Tenth Problem.
3. OPEN: Determine which subsets of F_i make this decidable? Σ^1_1-complete? Other?

Didn't Need Full Strength of Ramsey

The colorings we applied Ramsey to were of a certain type:

Definition

A coloring of the edges of K_n or K_{N} is transitive if, for every $i < j < k$, if $COL(i,j) = COL(j,k)$ then both equal $COL(i,k)$.

1. Our colorings were transitive.
2. Transitive Ramsey Thm is weaker than Ramsey's Thm.

Transitive Ramsey Weaker than Ramsey

TR is Transitive Ramsey, R is Ramsey.

1. Combinatorially: $R(k,c) = c^{\Theta(ck)}$, $TR(k,c) = (k-1)^c + 1$. This may look familiar

Transitive Ramsey Weaker than Ramsey

TR is Transitive Ramsey, R is Ramsey.

1. Combinatorially: $R(k,c) = c^{\Theta(ck)}$, $TR(k,c) = (k-1)^c + 1$. This may look familiar $TR(k,2) = (k-1)^2 + 1$ is Erdös-Szekeres Theorem. More usual statement: For any sequence of $(k-1)^2 + 1$ distinct reals there is either an increasing or decreasing subsequence of length k.

TR is Transitive Ramsey, R is Ramsey.

1. Combinatorially: $R(k,c) = c^{\Theta(ck)}$, $TR(k,c) = (k-1)^c + 1$. This may look familiar $TR(k,2) = (k-1)^2 + 1$ is Erdös-Szekeres Theorem. More usual statement: For any sequence of $(k-1)^2 + 1$ distinct reals there is either an increasing or decreasing subsequence of length k.
2. Computability: There exists a computable 2-coloring of K_ω with no computable homogeneous set (can even have no Σ_2 homogeneous set). For every transitive computable c-coloring of K_ω there exists a computable homogeneous set (folklore).

Transitive Ramsey Weaker than Ramsey

TR is Transitive Ramsey, R is Ramsey.

1. Combinatorially: $R(k,c) = c^{\Theta(ck)}$, $TR(k,c) = (k-1)^c + 1$. This may look familiar $TR(k,2) = (k-1)^2 + 1$ is Erdös-Szekeres Theorem. More usual statement: For any sequence of $(k-1)^2 + 1$ distinct reals there is either an increasing or decreasing subsequence of length k.
2. Computability: There exists a computable 2-coloring of K_ω with no computable homogeneous set (can even have no Σ_2 homogeneous set). For every transitive computable c-coloring of K_ω there exists a computable homogeneous set (folklore).
3. Proof Theory: Over the axiom system RCA_0, R implies TR, but TR does not imply R.

Summary

1. Ramsey Theory can be used to prove some simple programs terminate that seem harder to do my traditional methods. Interest to PL.
2. Some to subcases of TERMINATION PROBLEM are decidable. Of interest to PL and Logic.
3. Full strength of Ramsey not needed. Interest to Logicians and Combinatorists.