The Time of Space Invaders Will Come to Pass

A CS1 Functional Video Game Journey from Structural Recursion to Generative and Accumulative Recursion

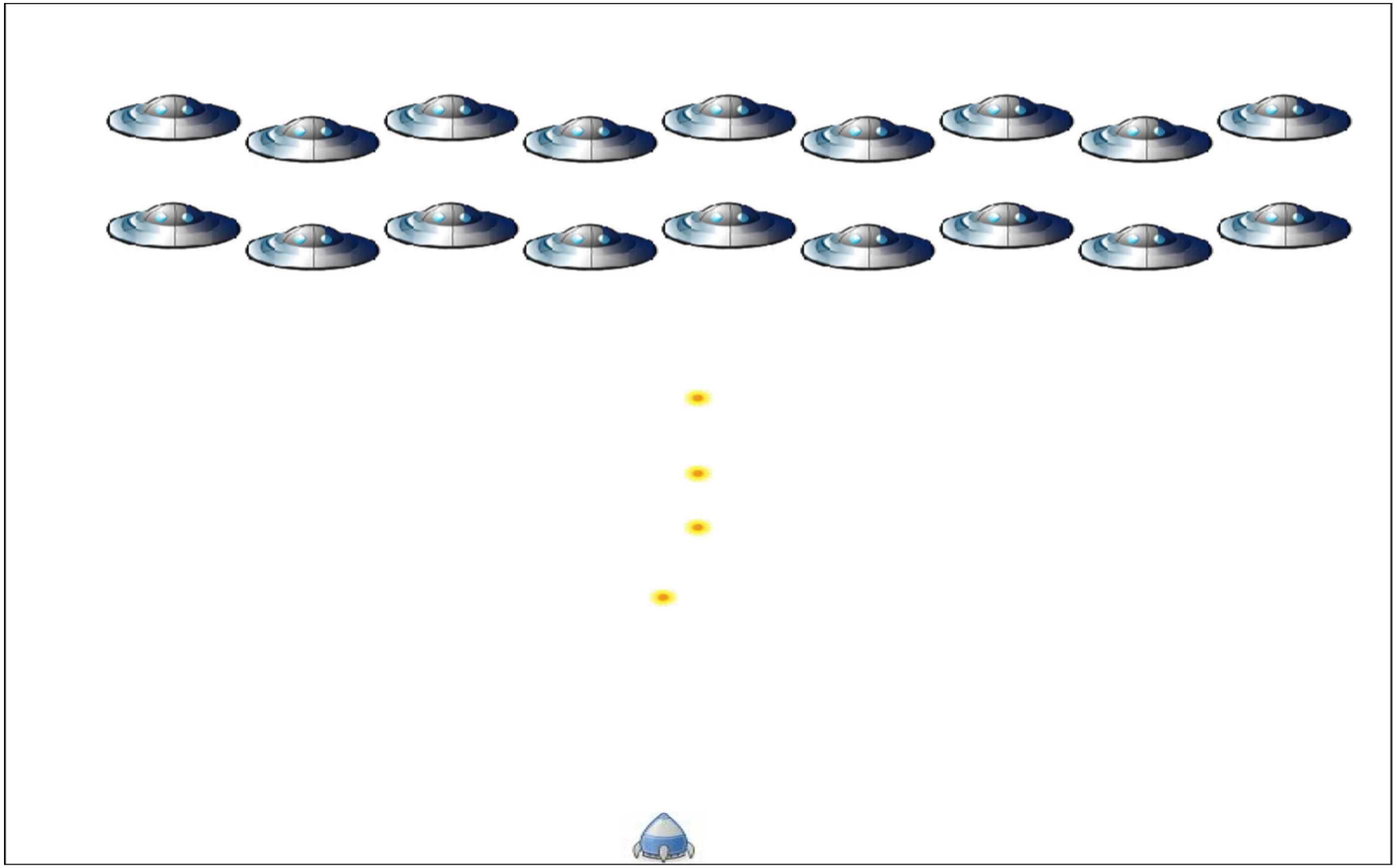
or

Achieving the Impossible!

Marco T. Morazán
Seton Hall University

Space Invaders by CS1 Students

- What do we do after students program Space Invaders?



Functional Video Games & CS1

- Functional Video Games in CS1
  - Flourishing trend
  - Used by universities and high schools
  - Program by Design using *How to Design Programs*

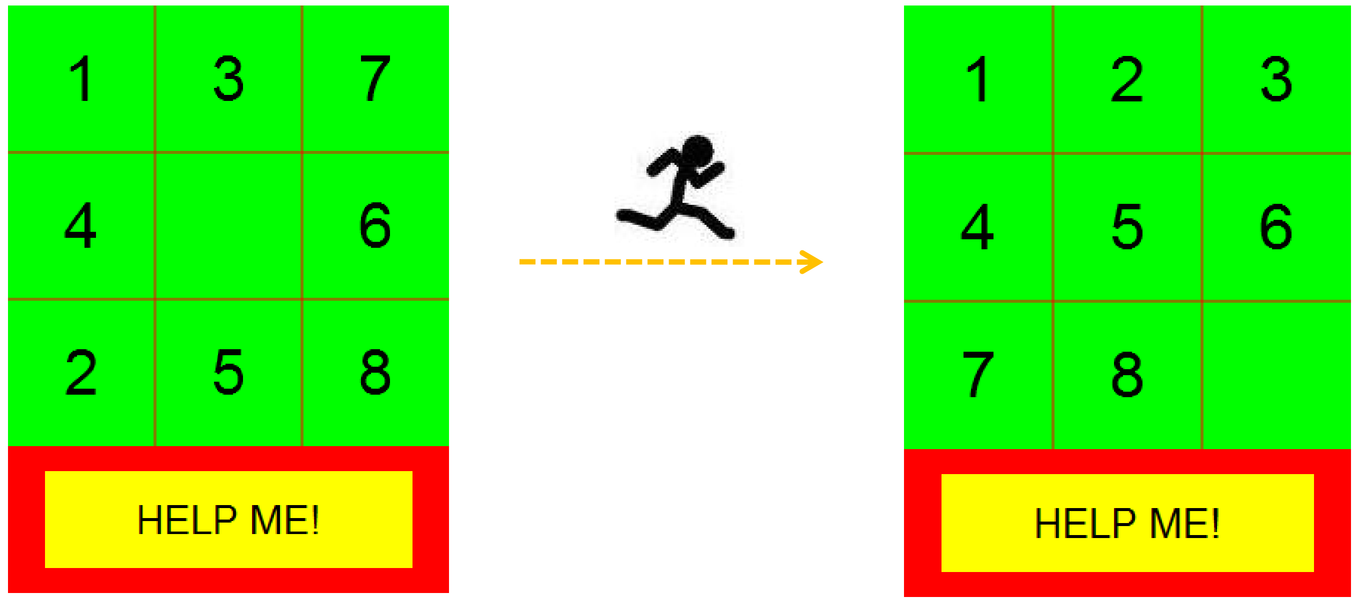
- Why is this successful?
  - Students get excited and can be creative
  - Students can go home and brag about what they have done!
  - No need to reason about state
  - Students learn to reason algorithms into existence using *Design Recipes*

Functional Video Games & CS1

- Design Recipe
  - Steps to follow to design functions based
  - From blank screen to working solution
- A great deal of examples using structural recursion
  - Space Invaders, Snake, Putting out fires
- There is more than structural recursion
- How to transition to Generative and Accumulative Recursion?
  - Harness the enthusiasm for video games
  - Reinforce lessons on structural recursion and abstraction
  - Few examples using video games in the literature

The N-Puzzle

Example



- Universal, easy to understand, easy to scale
- Help button to rescue those that are stuck
- Demonstrate that informed heuristic search strategies are within the grasp of CS1 students

The First Encounter in Class

- Students have studied
  - primitive data
  - structures
  - structural recursion (e.g., on lists, trees, and natural numbers)
  - abstraction (e.g. map, filter, build-list, and other basic HOFs)
  - Have implemented Space Invaders or Snake or ...

The First Encounter in Class

- What is changing in the game? How can it be represented?

  A board is either: (use BNF grammar????)

  1. empty
  2. (cons number b), where b is a board

  Template for functions on boards:

```
(define (f-on-board a-board)
   (cond   [(empty? a-board) …]
           [else …(first a-board)…(rest a-board)]))
```

- Brings the game into familiar territory!

The First Encounter in Class

- To get started ask students to perform task that are familiar
  - reinforce lessons on structural recursion and abstraction

```
(define WIN (build-list N (lambda (n)
                                     (cond [(< n (- N 1)) (+ n 1)]
                                           [else 0]))))
```

The First Encounter in Class

- To get started ask students to perform task that are familiar
  - reinforce lessons on structural recursion and abstraction

```
; get-blank-pos: board → number
; Purpose: To find the position of the blank
(define (get-blank-pos l)
  (cond [(empty? l) (error 'get-blank-pos "Blank not found")]
        [(= (car l) BLANK) 0]
        [else (add1 (get-blank-pos (cdr l)))]))
```

The First Encounter in Class

- To get started ask students to perform task that are familiar
  - reinforce lessons on structural recursion and abstraction

```
; swap-tiles: board natnum natnum → board
; Purpose: To swap the given tiles in the given board
(define (swap-tiles w i j)
  (build-list N (lambda (n)
                   (cond [(= n i) (list-ref w j)]
                         [(= n j) (list-ref w i)]
                         [else (list-ref w n)]))))
```

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- What does it mean to find a solution when the help button is hit?

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- What does it mean to find a solution when the help button is hit?
  - Find a sequence of moves from **b** to **WIN**
  - Find a solution from a successor of **b** to **WIN** and add move from **b** to the successor of **b**
  - Students easily see that recursion is required

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- What does it mean to find a solution when the help button is hit?
  - Find a sequence of moves from **b** to **WIN**
  - Find a solution from a successor of **b** to **WIN** and add move from **b** to the successor of **b**
  - Students easily see that recursion is required
- How do you select a successor of **b**?
  - Students have reasoned their way into generative recursion
  - The sub-problem is not based on the structure of **b** (nor is smaller)

Finding a Solution

- Selecting a successor
  - introduce students to heuristics
    - estimate how many moves to **WIN**
    - pick best successor
    - hope it leads to **WIN**

- The Manhattan distance of a board is the sum of how far away each tile is from its correct position
  - structural recursion on natural numbers

Finding a Solution

```
; manhattan-distance: board --> number
; Purpose: To compute the Manhattan distance of the given board
(define (manhattan-distance b)
  (local
    [; distance: number number --> number
     ; Purpose: To compute the distance between the two tile positions
     (define (distance curr corr)
       (+ (abs (- (quotient curr (sqrt N)) (quotient corr (sqrt N))))
            (abs (- (remainder curr (sqrt N)) (remainder corr (sqrt N))))))
```

Finding a Solution

```
; manhattan-distance: board --> number
; Purpose: To compute the Manhattan distance of the given board
(define (manhattan-distance b)
  (local
    [ ...
     ; correct-pos: number --> number
     ; Purpose: To determine the correct position of the given tile
     (define (correct-pos n)
       (cond [(= n 0) (sub1 N)]
             [else (sub1 n)]))]
```

Finding a Solution

```
; manhattan-distance: board --> number
; Purpose: To compute the Manhattan distance of the given board
(define (manhattan-distance b)
  (local
    [...
     ...
     ; adder: number --> number
     ; Purpose: To add all the distances of each tile
     (define (adder pos)
       (cond [(= pos 0) 0]
             [else (+ (distance (sub1 pos)
                                (correct-pos (list-ref b (sub1 pos))))
                      (adder (sub1 pos)))]))]
  (adder N)))
```

Finding a Solution

- The Solver
  - given a board return a sequence (non-empty list of boards)
  - leads naturally to a depth-first search algorithm
  - If the given board is the winning board, then the solution is trivial
  - Otherwise, create sequence from the given board and the solution generated starting from the best child of the given board

Finding a Solution

```
; find-solution-dfs: board --> (listof boards)
; Purpose: To find a solution to the given board using DFS
(define (find-solution-dfs b)
  (cond [(equal? b WIN) (list b)]
        [else
          (local [(define children (generate-children b))]
            (cons b (find-solution-dfs (best-child children))))]))
```

Finding a Solution

```
; generate-children: board --> non-empty-list-of-boards
; Purpose: To generate a list of the children of the given board
(define (generate-children b)
  (local [(define blank-pos (get-blank-sq-num b))]
    (map (lambda (p)
              (swap-tiles b blank-pos p))
           (blank-neighs blank-pos))))
```

Reinforces lessons on abstraction over lists

Finding a Solution

```
; best-child: non-empty-list-of-boards --> board
; Purpose: To find the board with the board with the smallest
;    Manhattan distance in the given non-empty list of boards
(define (best-child lob)
  (cond [(empty? (rest lob)) (car lob)]
        [else
          (local [(define best-of-rest (best-child (rest lob)))]
            (cond [(< (manhattan-distance (car lob))
                      (manhattan-distance best-of-rest))
                   (car lob)]
                  [else best-of-rest]))]))
```

Example 1

Example 2 (little man works forever)

Finding a Solution

- What have we accomplished?
  - Reinforces lessons on structural recursion
  - Introduced students to generative recursion and DFS
  - Introduced students to heuristic-based programming
  - Got students interested in all of the above via a functional video game

There is more!

Finding a Solution

- Reinforced the value of testing and iterative refinement
  - Testing reveals that solution is not found for all legal boards!
  - CS1 students can understand why!

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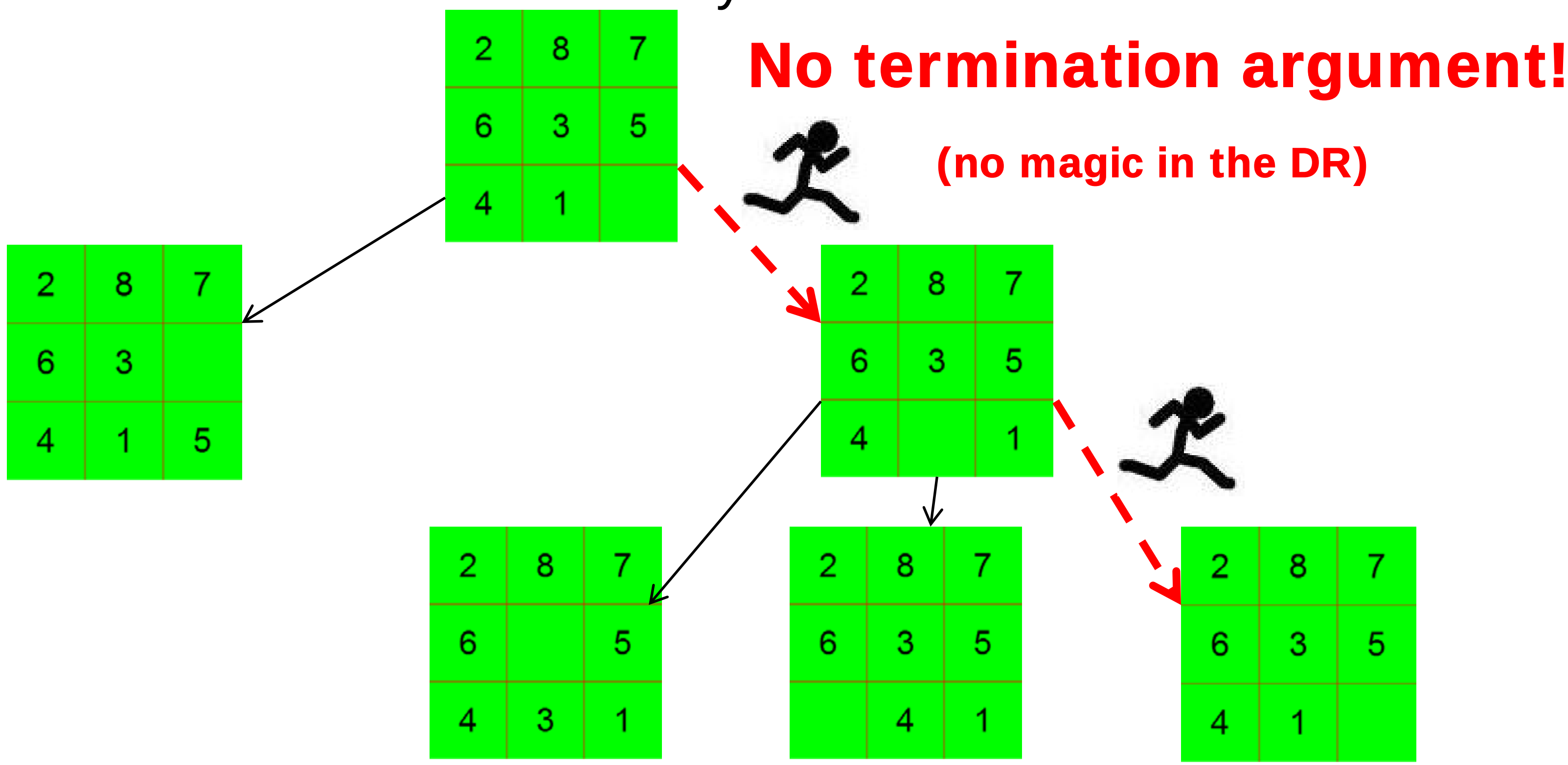

Refining the Solution

- Lead students to believe all sequences must be explored
  - Requires *remembering* all paths generated
  - Welcome to **accumulative recursion**!

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- Lead students to believe all sequences must be explored
  - Requires *remembering* all paths generated
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- Introduce students to BFS
  - Keep all sequences in order by length (introduce Qs????)
  - Build using work done for DFS solver
- The basic idea
  - if the first board in the first sequence is WIN, return the first sequence
  - Otherwise, generate new sequences using the successors of the first board in the first sequence

Refining the Solution

```
; find-solution-bfs: board → lseq
; Purpose: To find a solution to the given board
(define (find-solution-bfs b)
  (local
    [; search-paths: lseq → seq
     ; Purpose: To find a solution to b by searching all possible paths
     ; ACCUMULATOR INVARIANT:
     ;       paths is a list of all seqs generated so far starting at b from
     ;       from the shortest to the longest in reversed order
    (define (search-paths paths)
          (cond [(equal? (first (first paths)) WIN) (car paths)]
                [else
                  (local [(define chldrn (generate-children (first (first paths))))
                          (define new-paths (map (lambda (c) (cons c (first paths))) chldrn))]
                    (search-paths (append (rest paths) new-paths)))]))]
     (reverse (search-paths (list (list b))))))
```

EXAMPLE 1

EXAMPLE 2

Further Refining the Solution

- Nothing is worse than a slow video game!

- The problem
  - Exponential growth
    - after 10 moves the number of sequences being searched surpasses 2^{10}
    - after 20 moves it surpasses 2^{20}

Further Refining the Solution

- Is searching all possible sequences and searching all possible sequences at the same time necessary?
  - Most students can not answer and say yes

Further Refining the Solution

- Is searching all possible sequences and searching all possible sequences at the same time necessary?
  - Most students can not answer and say yes

- Two main ideas
  - not every sequence needs to be explored
    - visited successors can be ignored
  - explore the most promising sequence first

Further Refining the Solution

```
(define (find-solution-a-star b)
(local
    [(define (find-best-seq seqs)
          (cond [(empty? (rest seqs)) (first seqs)]
                   [else
                      (local [(define best-of-rest (find-best-seq (rest seqs)))]
                                 (cond [(< (manhattan-dist (first (first seqs)))
                                              (manhattan-dist (first best-of-rest)))
                                          (first seqs)]
                                         [else best-of-rest]))])]))
```

Further Refining the Solution

```
(define (find-solution-a-star b)
(local
    [...
     (define (search-paths visited paths)
       (local [(define bstseq (find-best-seq paths))]
              (cond [(equal? (first best-path) WIN) bstseq]
                    [else (local
                           [(define children (filter (lambda(c)(not(member c visited)))
                                                      (generate-children (first bstseq))))
                            (define new-seqs (map (lambda (c) (cons c bstseq))
                                                  children))]
                           (search-paths
                                 (cons (first bstseq) visited)
                                 (append new-seqs (rem-path bstseq paths))))])))]
     (reverse (search-paths '() (list (list b))))))
```

EXAMPLE

Related Work

- HtDP (the blue book)
  - Presents DRs for generative and accumulative recursion
    - Generative recursion
      - move away from structural recursion
      - recursion does not operate on part of the input
    - Accumulative recursion
      - Solves the problem of loss of knowledge

Related Work

- Soccer-Fun (Achten)
  - Play soccer
  - Used to teach FP to students sophomores
  - Not used in CS1, but used to motivate HS students
- Yampa (Courtney, Nilsson, & Peterson)
  - program reactive systems such as video games
  - Used to teach FP to students already exposed to programming (not recently)

Related Work

- N-Puzzle (Markov et al.)
  - used in AI & Machine Learning courses
  - used in Data Structures and Algorithms course
- Informed Heuristic Searching in CS1
  - Nijmegen: Exposure, but no implementation
  - Utrecht: CS majors in second year
  - Others: Intro to AI

Wishlist

- Student languages & HtDP with built-in
  - Queues
  - Stacks
- HtDP introducing BNF grammars
  - Good for CS majors

Conclusions

- In CS1
  - make the transition from structural recursion to generative & accumulative recursion using a video game as motivation
  - Make FP relevant early in CS development
  - informed heuristic search strategies are for CS1 students
    - CS1 students can reason such an algorithm into existence
    - CS1 students can be enthusiastic about implementation

Conclusions

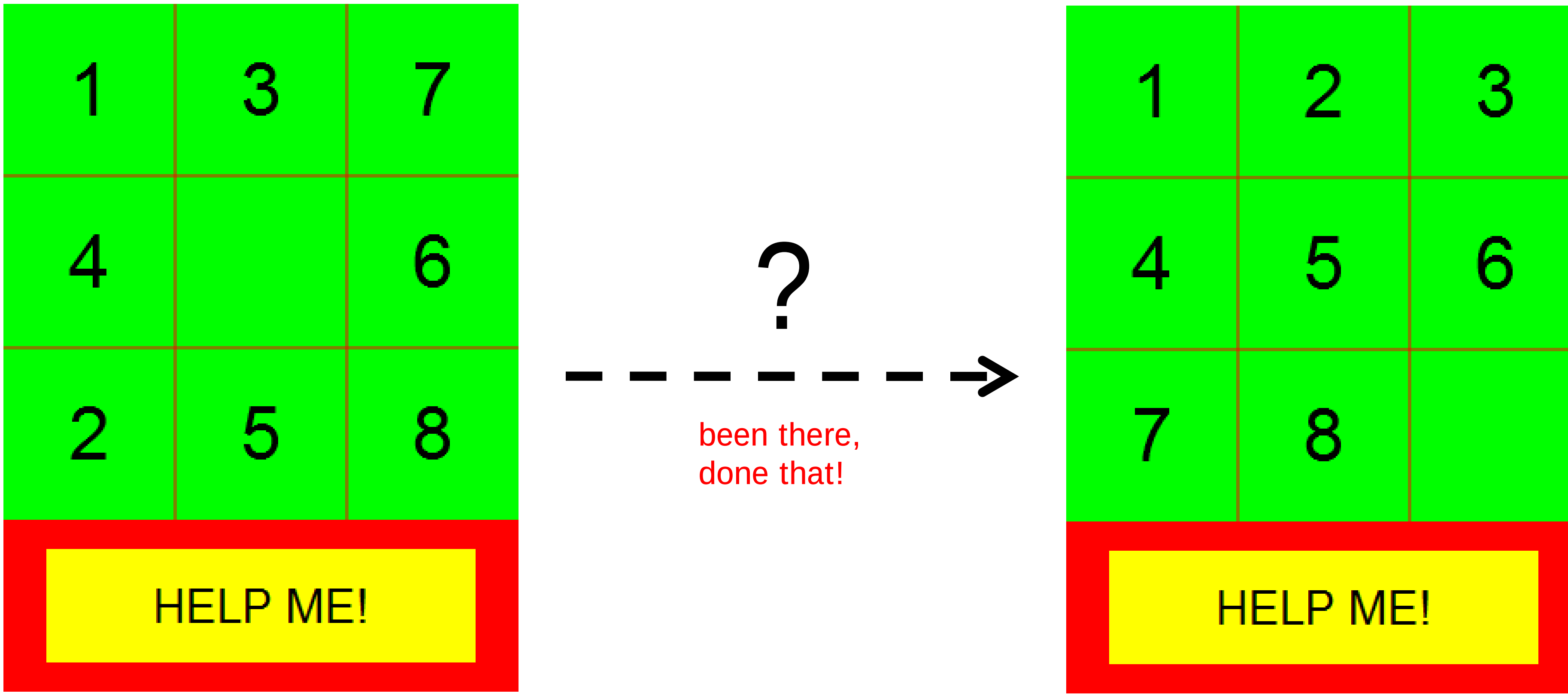
- In CS1
  - make the transition from structural recursion to generative & accumulative recursion using a video game as motivation
  - Make FP relevant early in CS development
  - informed heuristic search strategies are for CS1 students
    - CS1 students can reason such an algorithm into existence
    - CS1 students can be enthusiastic about implementation
- Future Work
  - Distributed Programming in CS1 using functional video games
  - State-based video games (??????)

FP in Education

- Workshop @ TFP 2012
  - St. Andrews University, Scotland (K. Hammond)
  - Workshop @ TFP 2013, BYU, Utah? (J. McCarthy)

- IFL 2011
  - University of Kansas (Andy Gill)

☺ Any Questions? ☺



Copies of two papers available @ front table