Automated Repair of Binary and Assembly Programs for Cooperating Embedded Devices

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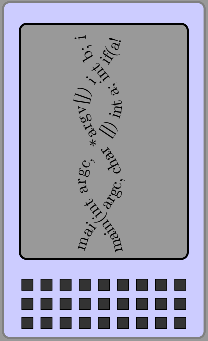
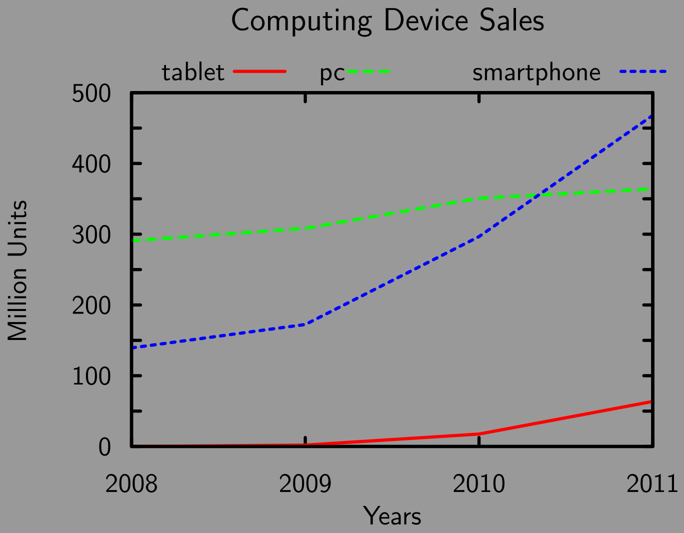
Outline

- Background
- Technical Approach
- Empirical Results
- Distributed Program Repair
- Discussion
- Conclusion



Embedded Devices



[Maier, 2011]

Embedded Devices

Resource Constraints

- Small disks
- Less memory
- Slow processors
- Slow, costly comm.

Genprog: Automatically Repairing Software Bugs

Use of algorithmic and heuristic methods to search for, generate, and evaluate program repairs.

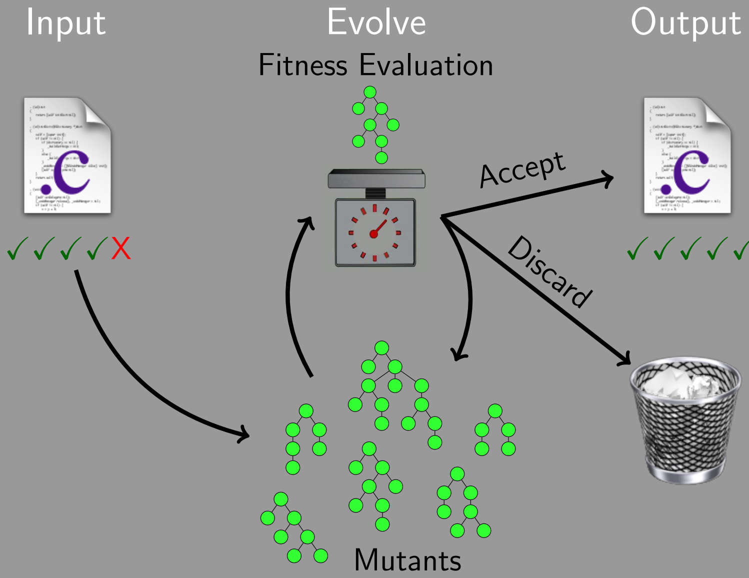
Strengths

- Repaired 55/105 bugs for $8 each [Le Goues et al., 2012a]
- Repairs multiple classes of bugs and security defects [Weimer et al., 2009]
- Wins human-competitive awards [Forrest et al., 2009; Le Goues et al., 2012b]

Limitations

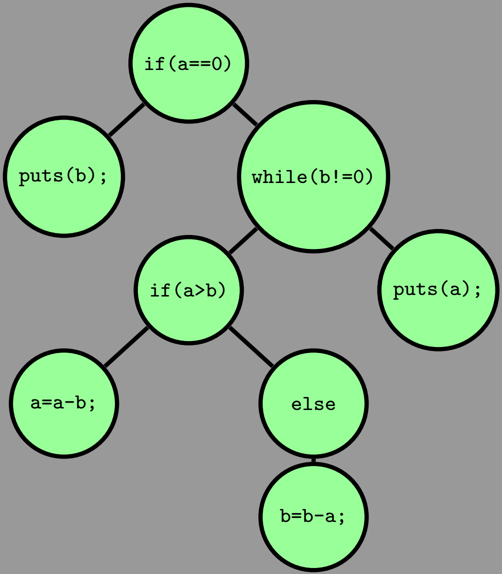
- Requires source code
- Requires build tool chain
- Requires program instrumentation
- Expensive fitness function (compilation, test execution)

Software Repair Algorithm: Baseline



Software Repair Algorithm: Contributions

- How do we mutate?
- Where do we mutate?



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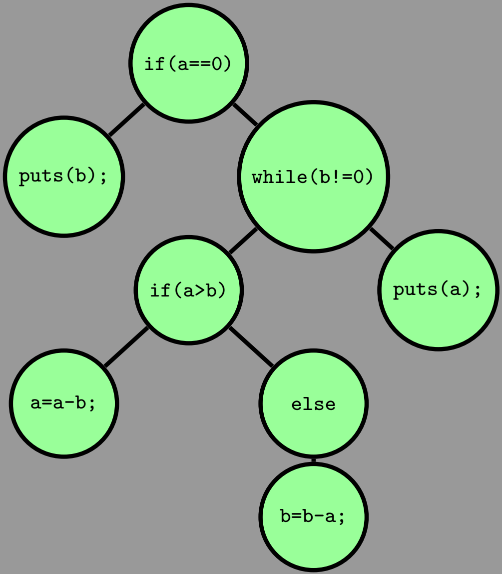
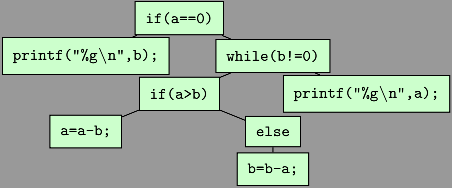


ASM and ELF Program Representations

Source

```c
if (a==0){
  printf("%g\n", b); }
else {
  while (b!=0){
    if (a>b){ a=a-b; }
    else    { b=b-a; } } }
printf("%g\n", a);
```

AST



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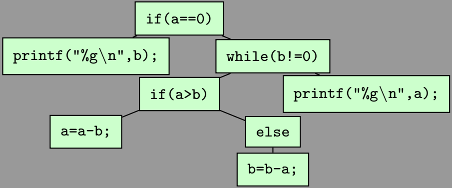

ASM

```
.file "gcd.c"
.globl main
.type main, @function
main:
.cfi_startproc
pushq %rbp
.cfi_def_cfa_offset 16
.cfi_offset 6, -16
movq %rsp, %rbp
.cfi_def_cfa_register 6
subq $48, %rsp
```

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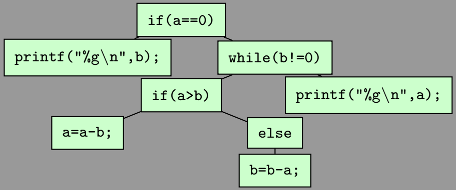

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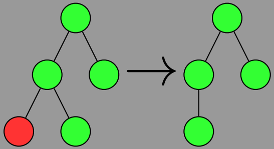
```

ELF

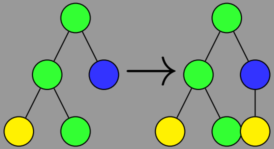
```
ELF\?
ELF header
program header table
section 1
...
.text section
[55] [48 89 e5] [48 83 ec 20]
[48 89 7d e8] [89 75 e4] [83
7d e4 01] [7e 60] ...
...
section n
section header table
```

ASM and ELF Program Mutations

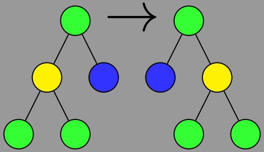
Delete



Insert



Swap



Delete:

```
movq 8(%rdx), %rdi
xorl %eax, %eax
movq %rdx, -80(%rbp)
addl $1, %r14d
call atoi
movq -80(%rbp), %rdx
movl %eax, (%r15)
addq $4, %r15
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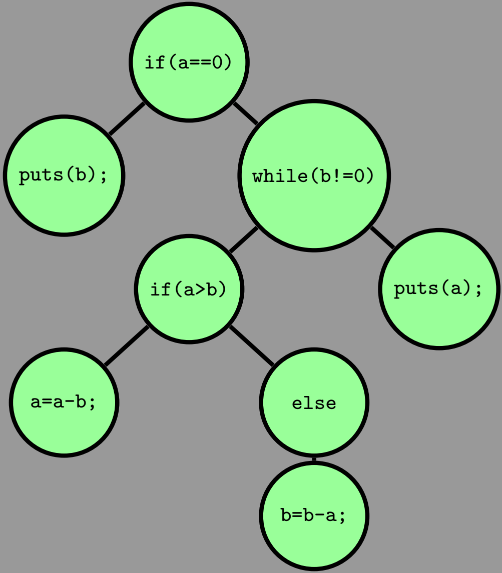
(... additional ELF bookkeeping ...)

Genprog: Automatically Repairing Software Bugs



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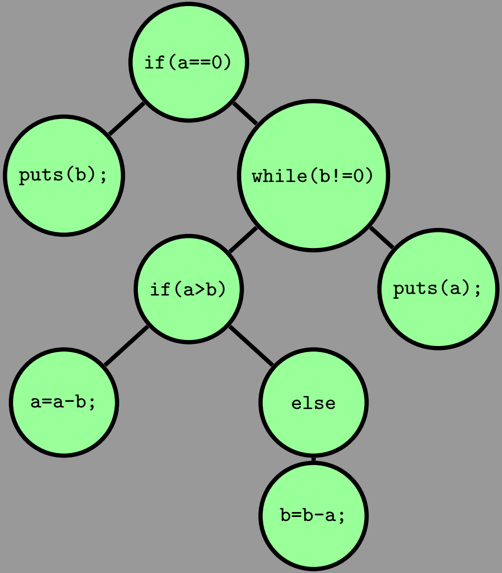

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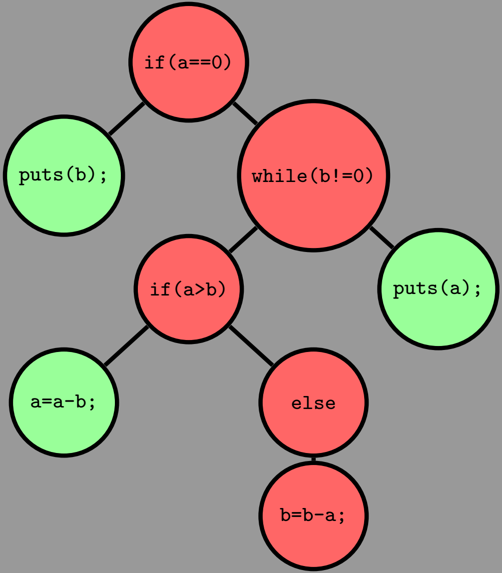
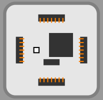


Fault Localization

Light Weight Fault Localization

1. Sample program counter.
2. Translate memory addresses to program offsets.
3. Smooth sample with Gaussian convolution.



CPU

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Machine-code Instructions

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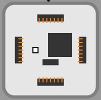

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Machine-code
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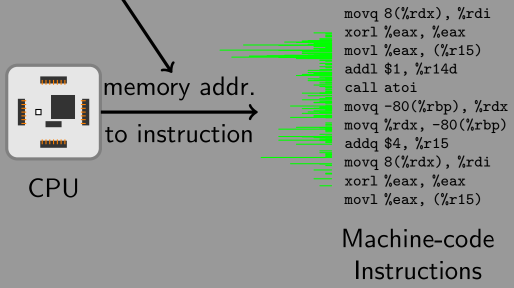

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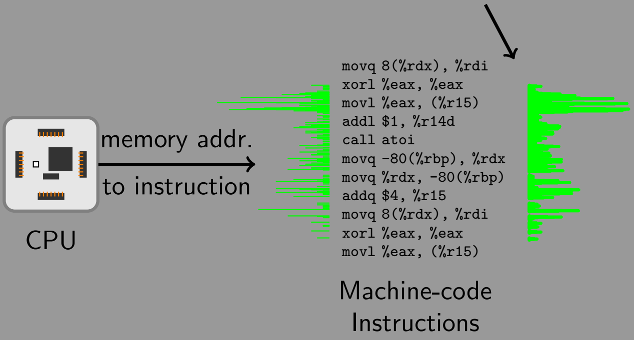
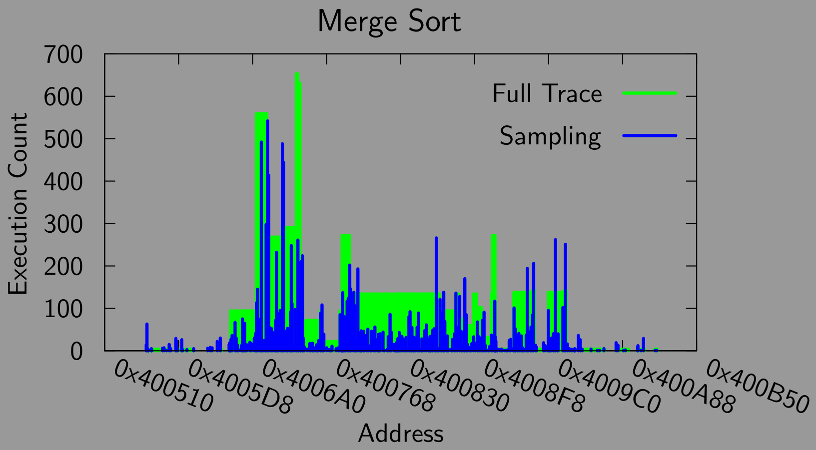


Fault Localization Comparison



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Benchmark Programs

Program	Program Description	Bug
`atris`	graphical tetris game	local stack buffer exploi
`ccrypt`	encryption utility	segfault
`deroff`	document processing	segfault
`flex`	lexical analyzer generator	segfault
`indent`	source code processing	infinite loop
`look svr4`	dictionary lookup	infinite loop
`look ultrix`	dictionary lookup	infinite loop
`merge`	merge sort	duplicate inputs
`merge-cpp`	merge sort (in C++)	duplicate inputs
`s3`	sendmail utility	buffer overflow
`uniq`	duplicate text processing	segfault
`units`	metric conversion	segfault
`zune`	embedded media player	infinite loop

Empirical Results

- Effective
- 62% faster runtime
- 95% smaller disk footprint
- 86% less memory

Total bugs repaired

Rep.	Num. Bugs
AST	13
ASM	12
ELF	11

Average success rate

100 runs per bug

Rep.	Success Rate
AST	78.17%
ASM	70.75%
ELF	65.83%

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Expected fitness evaluations

Rep.	Evaluations
AST	583.98
ASM	188.38
ELF	207.15

Total runtime

Rep.	Sec.
AST	229.50
ASM	278.30
ELF	74.20

Empirical Results

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Example: Merge Sort

Repair by representation

- AST, 2 of 4900 Swaps
- ASM, 1 of 280 Deletes

merge.c

```
if(left[l-mid-1]<=right[0]){
  result=list; }
else{/* fix:swap branches */
  result=merge(left,l-mid,
                    right,mid); }
```

merge.s

```
cmpl %eax, %edx ; fix: del.
jg   .L12
movq -72(%rbp), %rax
```

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Disk size

Rep.	Requirements
AST	Source code & build toolchain
ASM	Assembly code & linker
ELF	Compiled executable

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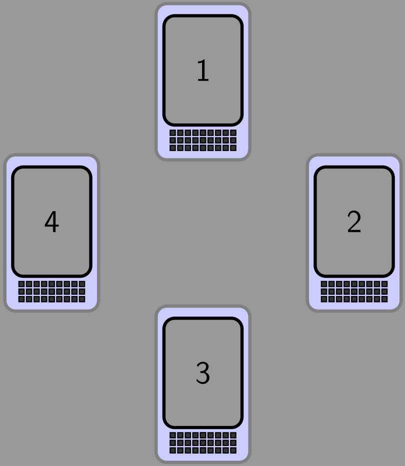
Working memory

Rep.	MB
AST	1402
ASM	756
ELF	200

Distributed Genetic Repair Algorithm



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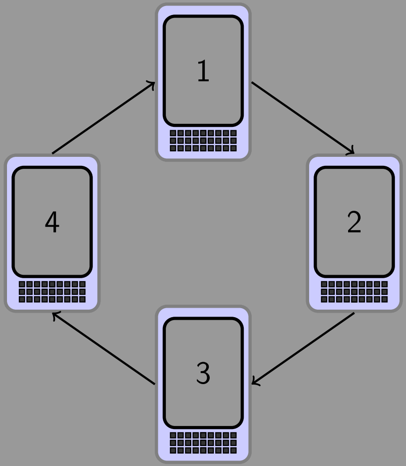

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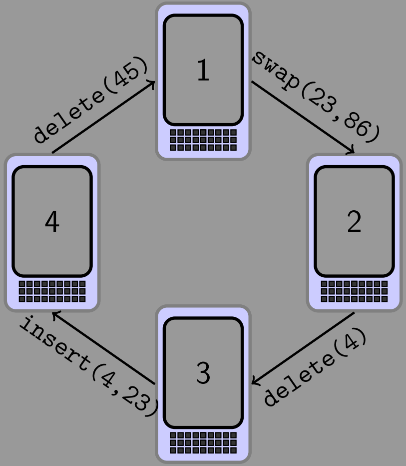

Distributed Genetic Repair Evaluation

Relative performance of DGA

# Nodes	Expected Fitness Evaluations	Wall Clock Seconds	w/SMS
1	1	1	1
2	0.94	0.89	1.07
3	0.84	0.67	0.81
4	0.80	0.55	0.63

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Discussion

- Search space
- System protection

ASM & ELF search space

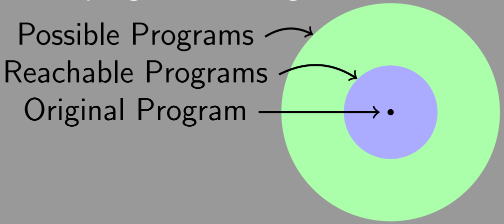
Program size

$\approx 3\times$ more assembly instructions than C statements

Search space size

$= |\text{alphabet}|^{\text{program size}}$

Possible program coverage



Discussion

- Search space
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System protection

- Arbitrary assembly is arbitrarily dangerous
- Light weight sandboxing (`ulimit` and `chroot`)

Conclusion

ASM and ELF representation

- Remove requirement for source code and build toolchain
- Language Agnostic; x86 or ARM assembly or ELF
- Change program repair search space
- Reduce resources; 95% smaller disk footprint, 86% less memory, 62% faster runtime

Distributed Genetic Program Repair

- Allows multiple devices to collaborate
- Fewer fitness evaluations and faster runtime

Conclusion

Take away

- Assembly mutations cause semantic changes!
- Software is not brittle!

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Take away

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Thank You

Contact

Name	Eric Schulte
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Homepage	`http://cs.unm.edu/~eschulte`

Code

Program Repair Tool	`http://genprog.cs.virginia.edu`
`ptrace` Tracer	`http://github.com/eschulte/tracer`
ELF (*C*)	`http://github.com/eschulte/rw-elf`
ELF (*Common Lisp*)	`http://github.com/eschulte/elf`

Bibliography

S. Forrest, W. Weimer, T. Nguyen, and C. Le Goues. A genetic programming approach to automated software repair. In Genetic and Evolutionary Computing Conference, 2009.

C. Le Goues, M. Dewey-Vogt, S. Forrest, and W. Weimer. A systematic study of automated program repair: Fixing 55 out of 105 bugs for $8 each. In International Conference on Software Engineering, 2012a.

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Backup Slides

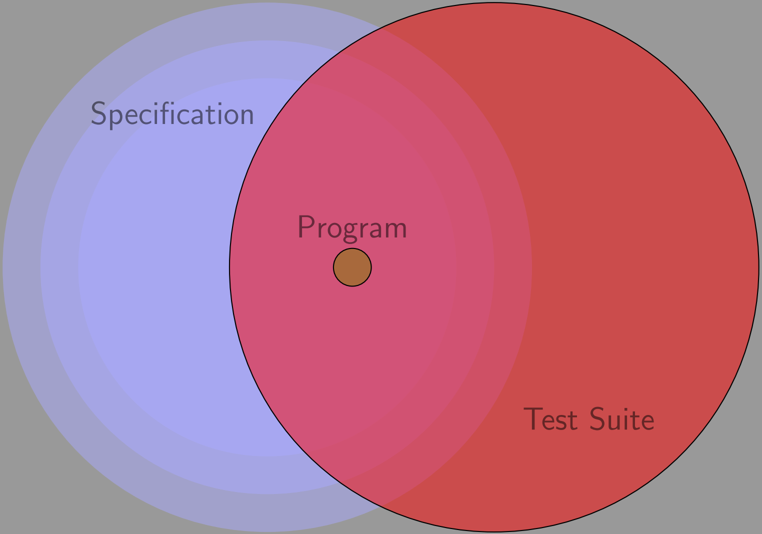
Backup: Wall Clock Times

Mean wall clock time in seconds to find a successful repair

	DGA		Naïve Parallel
# Nodes	Seconds	Rounds	Seconds
1			205.531
2	173.868	43.2	195.821
3	135.17	28.2	201.346
4	115.566	14.5	211.989

Backup: Software Mutational Robustness

Semantic Space, Specification & Test Suite



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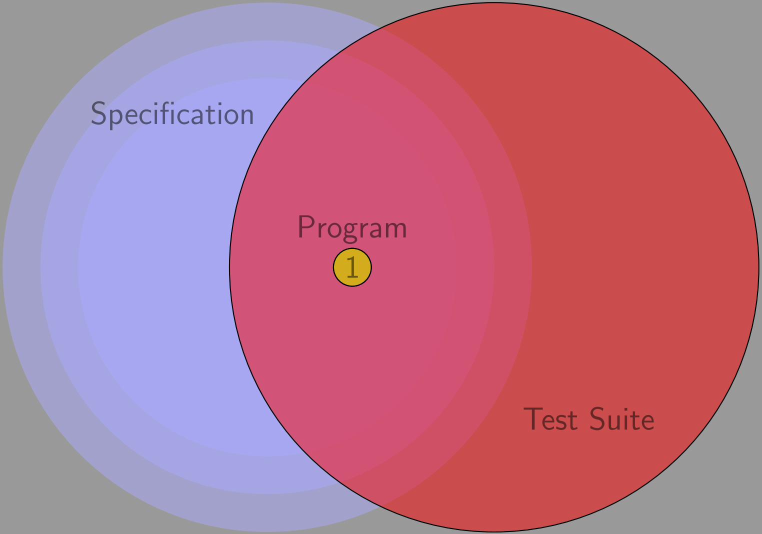

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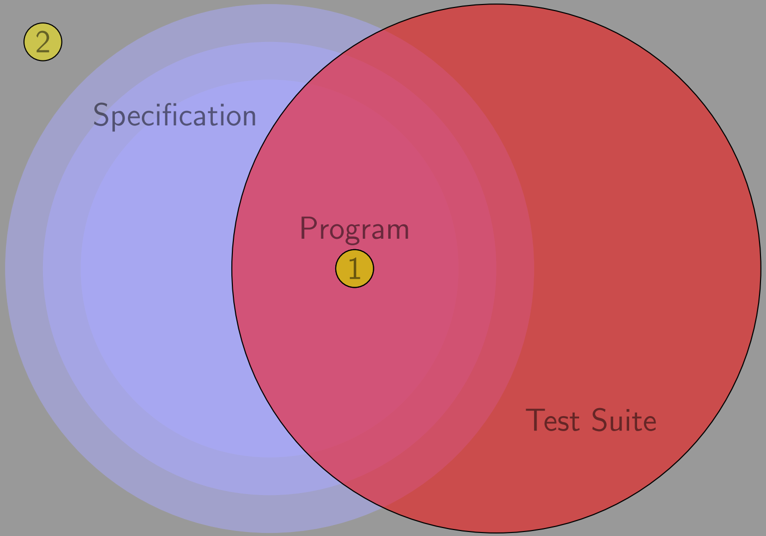

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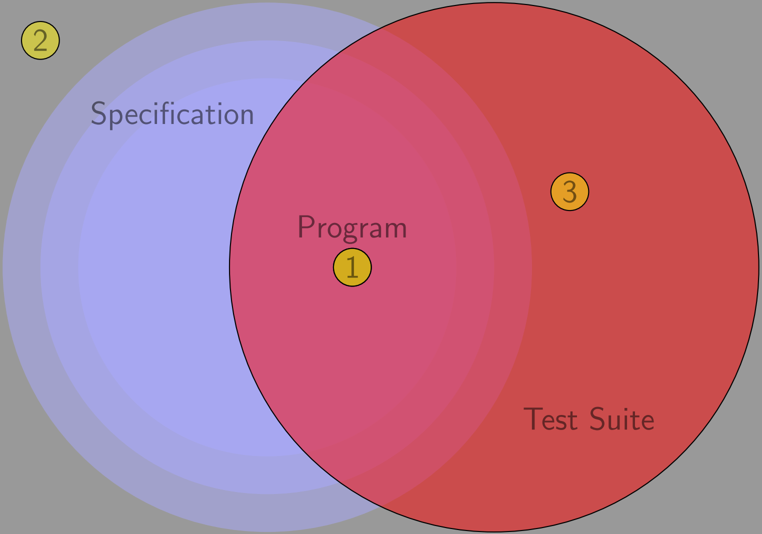

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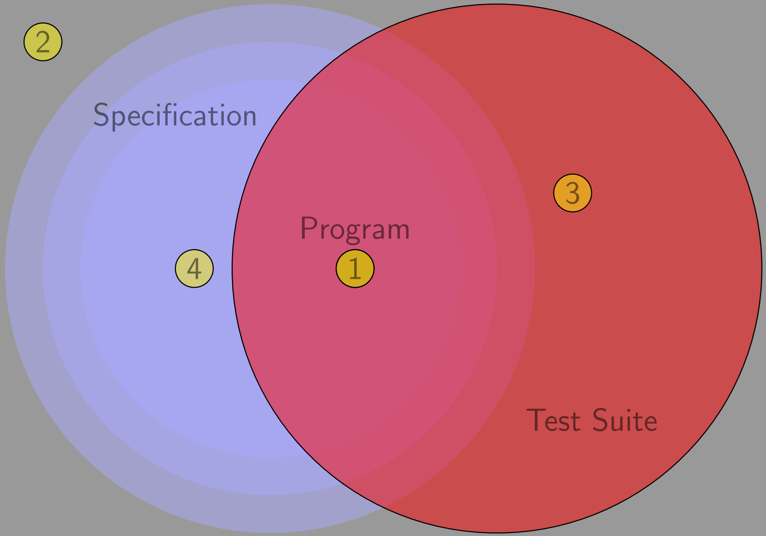

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