Securing software by enforcing data-flow integrity

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Software is vulnerable

- use of unsafe languages is prevalent
  - most “packaged” software written in C/C++
- many software defects
  - buffer overflows, format strings, double frees
- many ways to exploit defects
  - corrupt control-data: stack, function pointers
  - corrupt non-control-data:
    function arguments, security variables

defects are routinely exploited

Approaches to securing software

- remove/avoid all defects is hard
- prevent control-data exploits
  - protect specific control-data StackGuard, PointGuard
  - detect control-flow anomalies Program Shepherding, CFI
  - attacks can succeed without corrupting control-flow
- prevent non-control-data exploits
  - bounds checking on all pointer dereferences CRED
  - detect unsafe uses of network data
    Vigilante, [Suh04], Minos, TaintCheck, [Chen05], Argos, [Ho06]
  - expensive in software

no good solutions to prevent
non-control-data exploits

Data-flow integrity enforcement

- compute data-flow in the program statically
  - for every load, compute the set of stores that may produce the loaded data
- enforce data-flow at runtime
  - when loading data, check that it came from an allowed store
- optimize enforcement with static analysis

Data-flow integrity: advantages

- broad coverage
  - detects control-data and non-control-data attacks
- automatic
  - extracts policy from unmodified programs
- no false positives
  - only detects real errors (malicious or not)
- good performance
  - low runtime overhead

Outline

- data-flow integrity enforcement
- optimizations
- results

Data-flow integrity

- at compile time, compute reaching definitions
  - assign an id to every store instruction
  - assign a set of allowed source ids to every load
- at runtime, check actual definition that reaches a load
  - runtime definitions table (RDT) records id of last store to each address
  - on store(value,address): set RDT[address] to store's id
  - on load(address): check if RDT[address] is one of the allowed source ids
- protect RDT with software-based fault isolation

Example vulnerable program

```
int authenticated = 0;
char packet[1000];

while (!authenticated) {
  PacketRead(packet);

  if (Authenticate(packet))
    authenticated = 1;
}

 if (authenticated)
   ProcessPacket(packet);
```

buffer overflow in this function allows the attacker to set authenticated to 1

- non-control-data attack
- very similar to a real attack on a SSH server

Static analysis

- computes data flows conservatively
  - flow-sensitive intraprocedural analysis
  - flow-insensitive interprocedural analysis
    - uses Andersen's points-to algorithm
    - scales to very large programs
- same assumptions as analysis for optimization
  - pointer arithmetic cannot navigate between independent objects
  - these are the assumptions that attacks violate

Instrumentation

```
SETDEF authenticated 1
int authenticated = 0;
char packet[1000];

while (CHECKDEF authenticated in {1,8}
       !authenticated) {
  PacketRead(packet);

  if (Authenticate(packet)){
    SETDEF authenticated 8
    authenticated = 1;
   }
}
CHECKDEF authenticated in {1,8}
if (authenticated)
   ProcessPacket(packet);
```

check that authenticated was written here or here

Runtime: detecting the attack

Vulnerable program

```
SETDEF authenticated 1
int authenticated = 0;
char packet[1000];

while (CHECKDEF authenticated in {1,8}
       !authenticated) {
  PacketRead(pack  t);

  if (Authentic
    SETDEF authent
    authenticate
  }
}
CHECKDEF authenticated  n {1,8}
if (authenticated)
   ProcessPacket(packet);
```

Attack detected!
definition 7 not
in {1,8}

Memory layout

Also prevents control-data attacks

- user-visible control-data (function pointers,…)
  - handled as any other data
- compiler-generated control-data
  - instrument definitions and uses of this new data
  - e.g., enforce that the definition reaching a **`ret`** is generated by the corresponding **`call`**

Efficient instrumentation: SETDEF

- SETDEF _authenticated 1 is compiled to:

```
    lea  ecx,[_authenticated]
    test ecx,0C0000000h
    je   L
    int  3
L:  shr  ecx,2
    mov  word ptr [ecx*2+40001000h],1
```

get address of variable

prevent RDT tampering

set RDT[address] to 1

Efficient instrumentation: CHECKDEF

- CHECKDEF _authenticated {1,8} is compiled to:

get address of variable

```
lea  ecx,[_authenticated]
shr  ecx,2
mov  cx, word ptr [ecx*2+40001000h]
cmp  cx, 1
je   L
cmp  cx,8
je   L
int  3
L:
```

get definition id from RDT[address]

check definition in {1,8}

Optimization: renaming definitions

- definitions with the same set of uses share one id

```
SETDEF authenticated 1
int authenticated = 0;
char packet[1000];
while (
CHECKDEF authenticated in {1}8}
       !authenticated) {
  PacketRead(packet);
  if (Authenticate(packet)){
    SETDEF authenticated 8
    authenticated = 1;
   }
}
CHECKDEF authenticated in {1}8}
if (authenticated)
   ProcessPacket(packet);
```

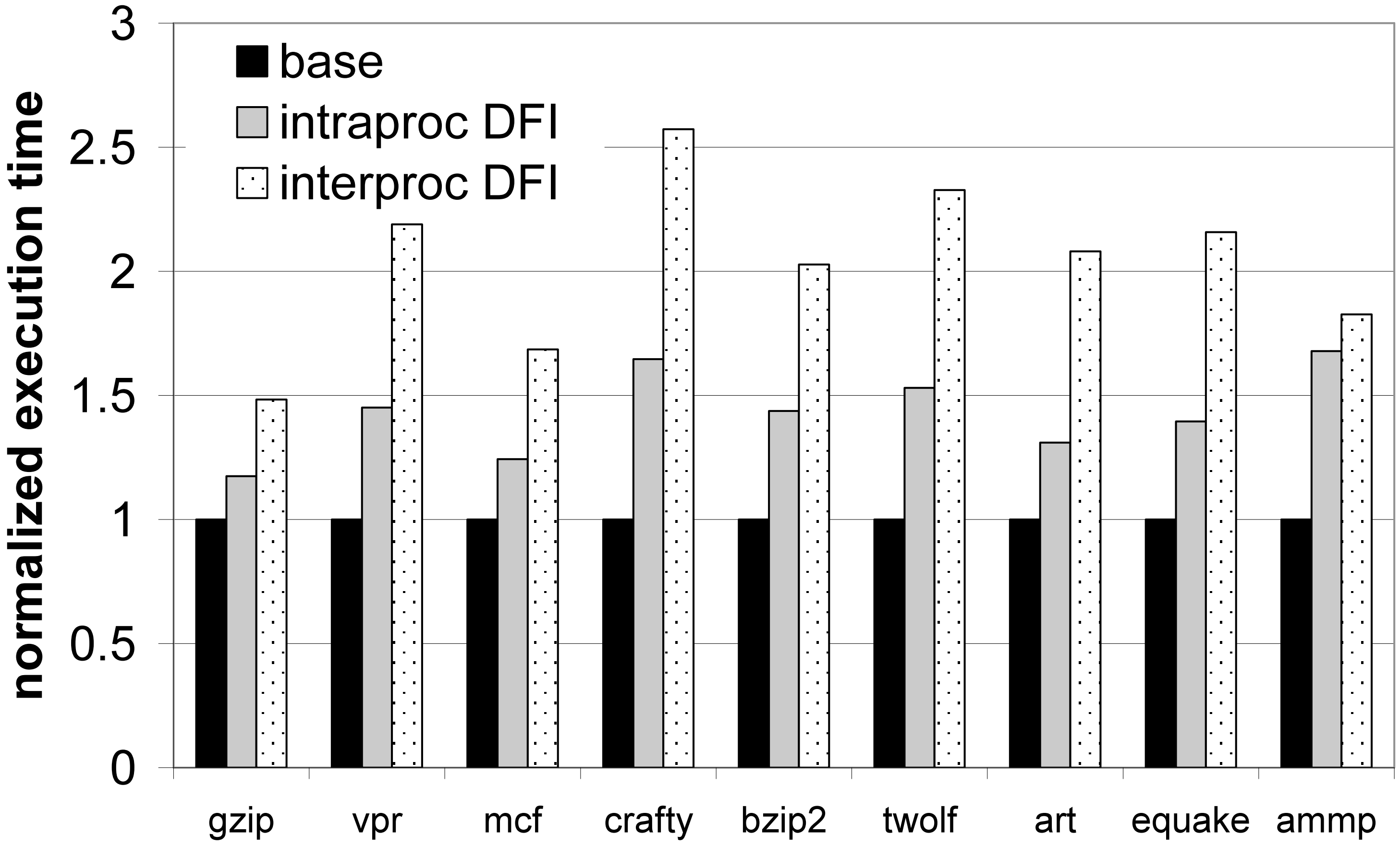
Other optimizations

- removing SETDEFs and CHECKDEFs
  - eliminate CHECKDEFs that always succeed
  - eliminate redundant SETDEFs
  - uses static analysis, but does not rely on any assumptions that may be violated by attacks
- remove bounds checks on safe writes
- optimize set membership checks
  - check consecutive ids using a single comparison

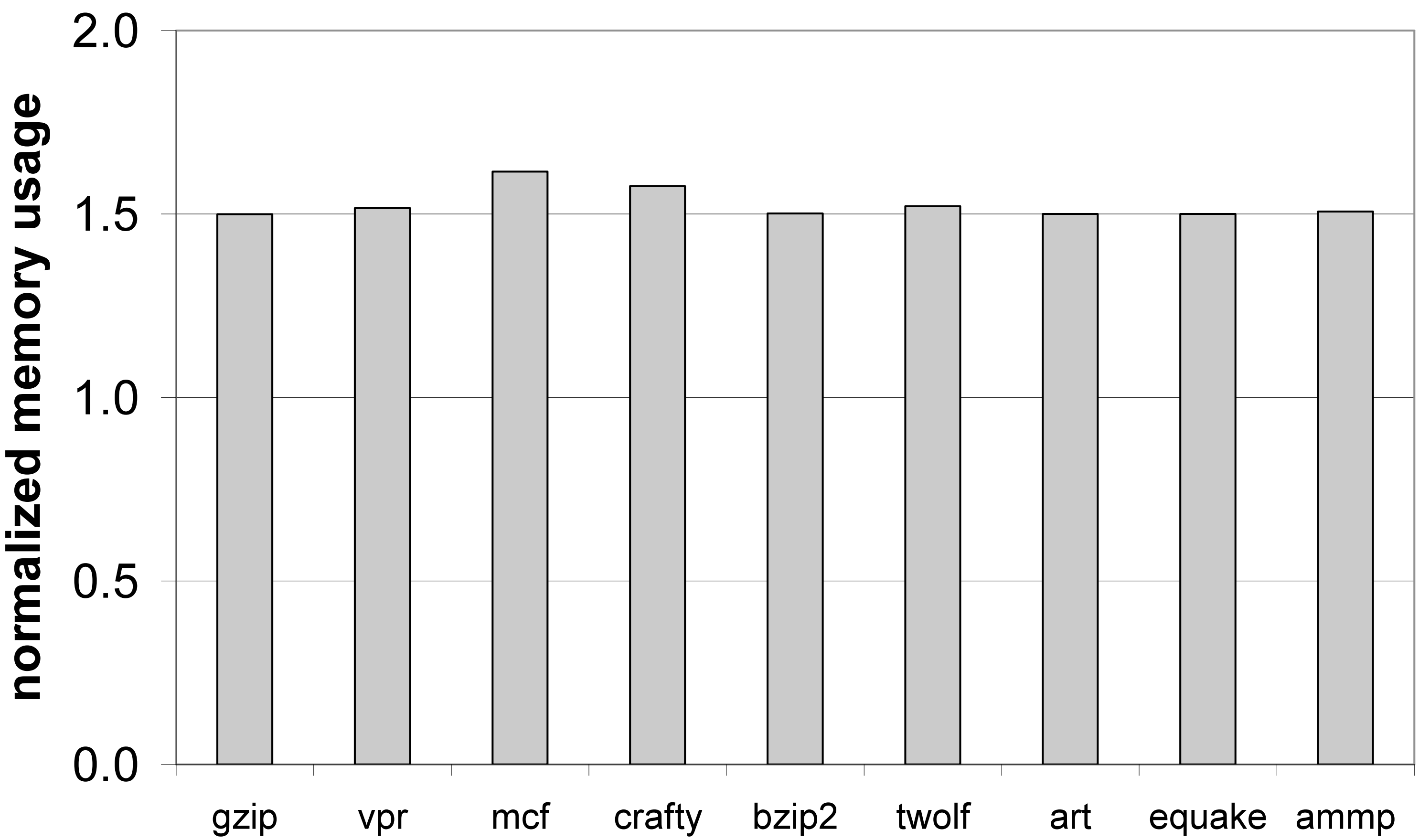
Evaluation

- overhead on SPEC CPU and Web benchmarks
- contributions of optimizations
- ability to prevent attacks on real programs

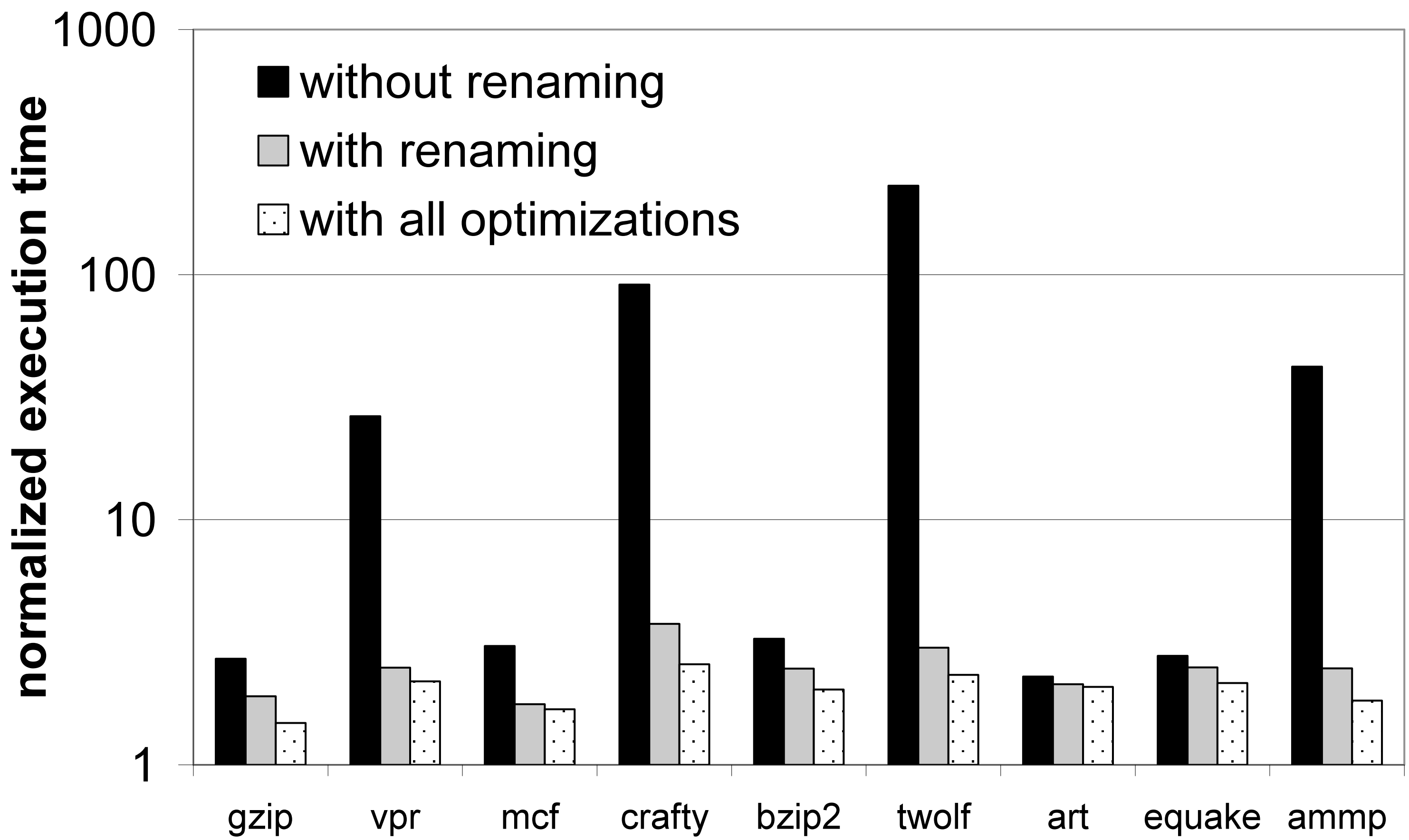
Runtime overhead



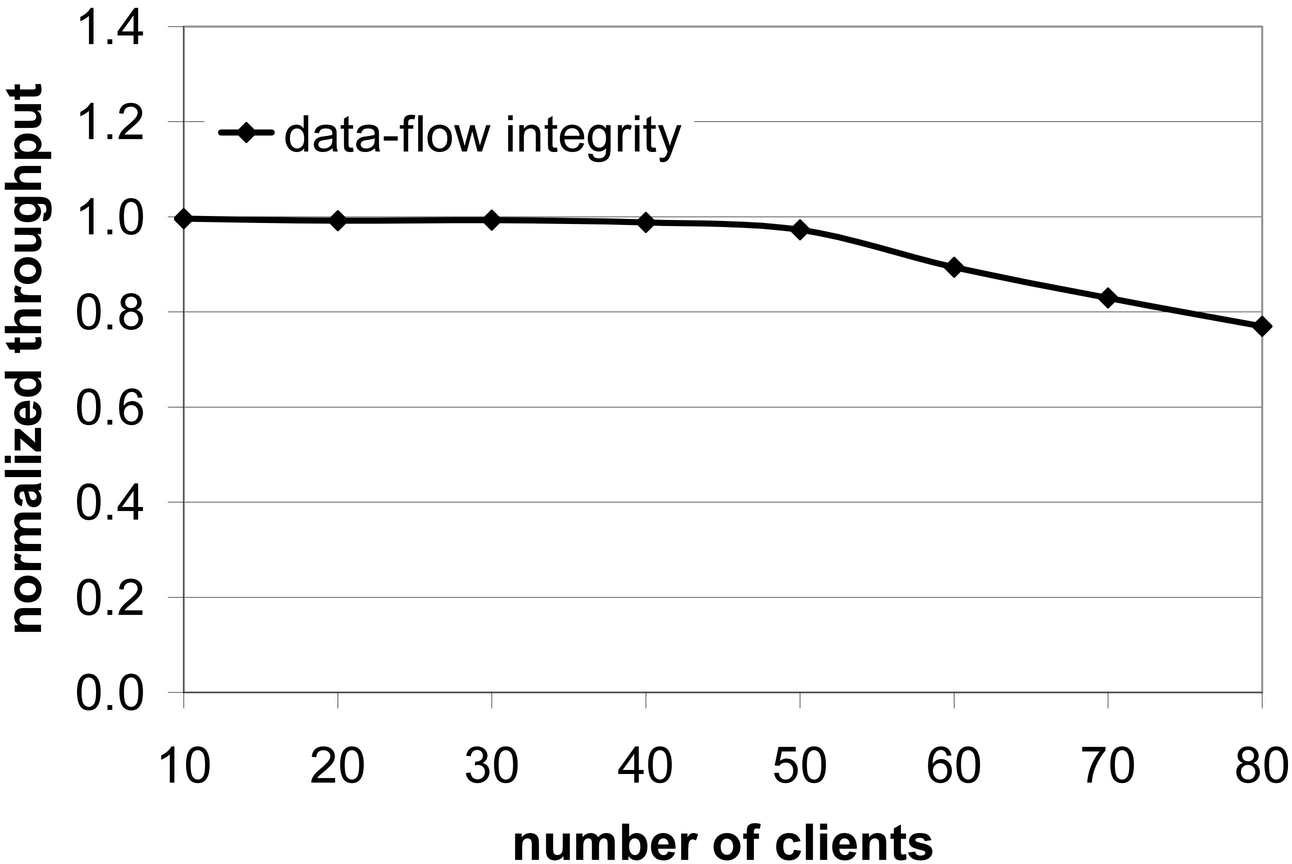
Memory overhead



Contribution of optimizations



Overhead on SPEC Web



maximum overhead of 23%

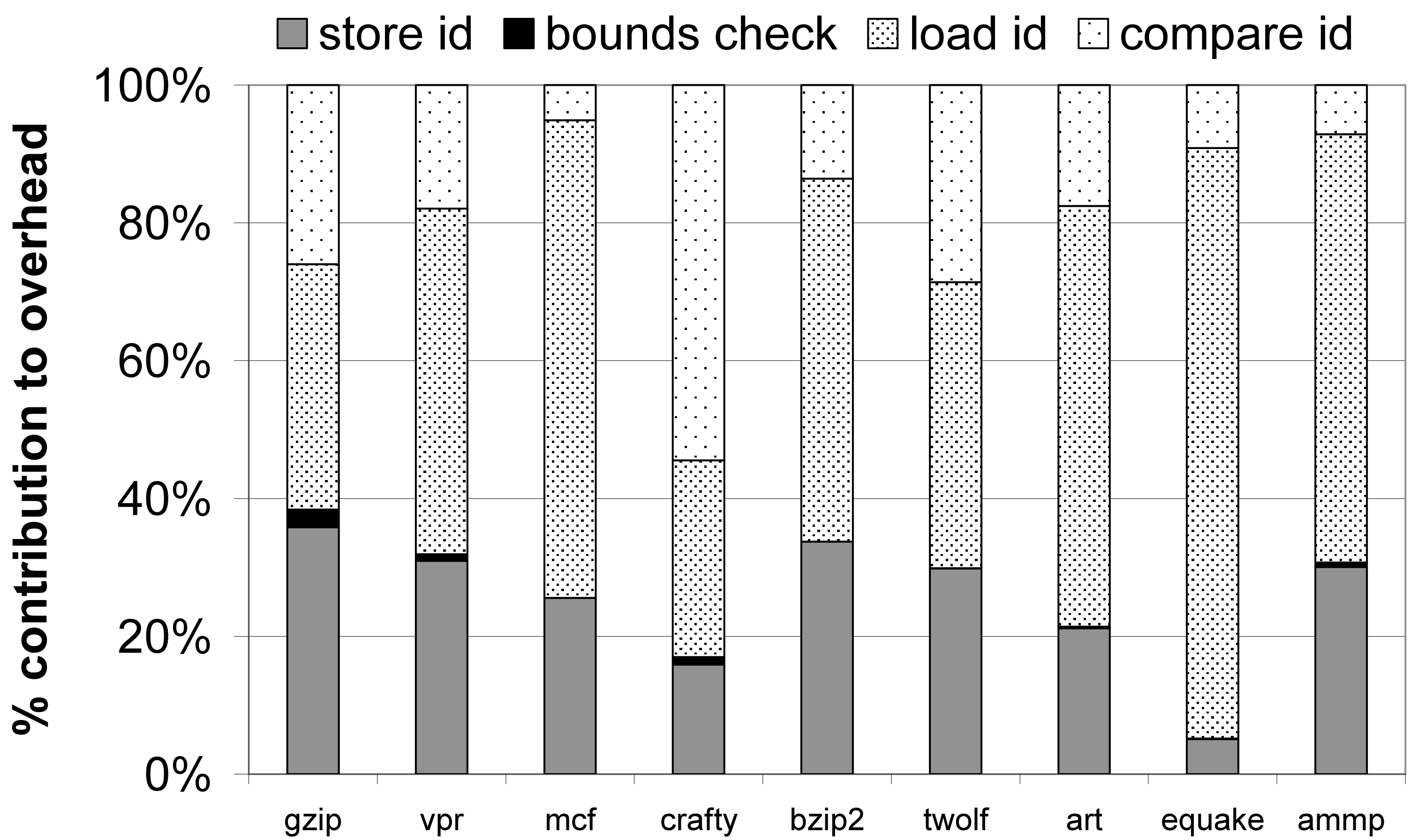
Preventing real attacks

Application	Vulnerability	Exploit	Detected?
NullHttpd	heap-based buffer overflow	overwrite cgi-bin configuration data	yes
SSH	integer overflow and heap-based buffer overflow	overwrite authenticated variable	yes
STunnel	format string	overwrite return address	yes
Ghttpd	stack-based buffer overflow	overwrite return address	yes

Conclusion

- enforcing data-flow integrity protects software from attacks
  - handles non-control-data and control-data attacks
  - works with unmodified C/C++ programs
  - no false positives
  - low runtime and memory overhead

Overhead breakdown



Contribution of optimizations