Code Size Reduction by Difference Classification and Customized Lookup Table Generation

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Importance of code size reduction for mobile devices

- Benefits of smaller text code size
  - Less memory usage, enabling more functionality to reside simultaneously in on-chip RAM
  - Improved instruction cache performance
  - Reduced instruction bus traffic
- Undesired side effects
  - Some optimizations can degrade performance
  - Apply these to less time-critical portions of code
- Extensive control code and switch-case constructs in wireless networking, modem, and protocol code
  - Reduce code size by detecting similarities and replacing "compile time constant" differences as dictionary lookups

Simplified example

```
extern func1(int x, int y);
extern func2(int x, int y);
extern func3(int x, int y);
extern func4(int x, int y);
extern func5(int x, int y);
extern func6(int x, int y);
extern int g_array[];
int test(int i, int x)
{
   int a;
   switch(i)
   {
     case 1: a = 27 + x; break;
     case 2: a = 55 + x; break;
     case 3: a = 1024 + x; break;
     case 4: a = 23 + x; break;
     case 5: a = 129 + x; break;
     case 6: a = 256 + x; break;
     case 7: a = g_array[1]; break;
     case 8: a = g_array[6]; break;
     case 9: a = g_array[2]; break;
     case 10: a = g_array[9]; break;
     case 11: a = g_array[5]; break;
     case 12: a = g_array[4]; break;

     case 13: a = func1(x,1); break;
     case 14: a = func2(x,1); break;
     case 15: a = func3(x,1); break;
     case 16: a = func4(x,1); break;
     case 17: a = func5(x,1); break;
     case 18: a = func6(x,1); break;
     default: a = i;  break;
   }
   return(a);
}
```

Assembly code by original Open64

```
test:
    r8=#(.rodata)
    r6=r0
    if (r0 >= #19)
     jump .Lt_0_2
    r8=add(r8,r0<<#2)
    r9=loadw(r8+#0)
    jumpr r9

.Lt_0_2:
    r0=r6
    return;

.Lt_0_19:
    r0=r1
    r1=#1
    call func6
    r6=r0
    jump .Lt_0_2
.Lt_0_18:
    r0=r1
    r1=#1
    call func5
    r6=r0
    jump .Lt_0_2
.Lt_0_17:
    r0=r1
    r1=#1
    call func4
    r6=r0
    jump .Lt_0_2
```

```
.Lt_0_16:
    r0=r1
    r1=#1
    call func3
    r6=r0
    jump .Lt_0_2
.Lt_0_15:
    r0=r1
    r1=#1
    call func2
    r6=r0
    jump .Lt_0_2
.Lt_0_14:
    r0=r1
    r1=#1
    call func1
    r6=r0
    jump .Lt_0_2

.Lt_0_13:
    r6=#(g_array+16)
    r6=loadw(r6+#0)
    jump .Lt_0_2
.Lt_0_12:
    r6=#(g_array+20)
    r6=loadw(r6+#0)
    jump .Lt_0_2
.Lt_0_11:
    r6=#(g_array+36)
    r6=loadw(r6+#0)
    jump .Lt_0_2
```

```
.Lt_0_10:
    r6=#(g_array+8)
    r6=loadw(r6+#0)
    jump .Lt_0_2
.Lt_0_9:
    r6=#(g_array+24)
    r6=loadw(r6+#0)
    jump .Lt_0_2
.Lt_0_8:
    r6=#(g_array+4)
    r6=loadw(r6+#0)
    jump .Lt_0_2
.Lt_0_7:
    r6=add(r1,#256)
    jump .Lt_0_2
.Lt_0_6:
    r6=add(r1,#129)
    jump .Lt_0_2
.Lt_0_5:
    r6=add(r1,#23)
    jump .Lt_0_2
.Lt_0_4:
    r6=add(r1,#1024)
    jump .Lt_0_2
.Lt_0_3:
    r6=add(r1,#55)          jump
.Lt_0_2

.Lt_0_1:
    r6=add(r1,#27)
    jump .Lt_0_2
```

ORIGINAL JUMP TABLE

```
.section
.rodata
.org 0x0

.word .Lt_0_2
.word .Lt_0_1
.word .Lt_0_3
.word .Lt_0_4
.word .Lt_0_5
.word .Lt_0_6
.word .Lt_0_7
.word .Lt_0_8
.word .Lt_0_9
.word .Lt_0_10
.word .Lt_0_11
.word .Lt_0_12
.word .Lt_0_13
.word .Lt_0_14
.word .Lt_0_15
.word .Lt_0_16
.word .Lt_0_17
.word .Lt_0_18
.word .Lt_0_19
```

Improved assembly code after detecting similarity and replacing differences using LUT

```
test:
   r8=#(.rodata)
   r6=r0

   if (r0 >= #19)
      jump .Lt_0_2

r8=add(r8,r0<<#2)
r9=loadw(r8+#0)

.Lt_Unchanged:
 if (r0 <= #0)
      jumpr r9

.Lt_SingleConst:
 if (r0 <= #6)
    jump .Lt_0_1

.Lt_MemOffset:
 if (r0 <= #12)
    jump .Lt_0_8

.Lt_SameCallSig:
 if (r0 <= #18)
     jump .Lt_0_14
```

```
.Lt_0_2:
  r0=r6
  return;

.Lt_0_14:
  r0=r1
  r1=#1
  callr r9
  r6=r0
  jump .Lt_0_2

.Lt_0_8:
  r6=#(g_array)
  r6=r6+r9
  r6=loadw(r6+#0)
  jump.Lt_0_2

.Lt_0_1:
  r6=add(r1,r9)
  jump .Lt_0_2
```

JUMP TABLE NOW PARTLY BECOMES LUT

```
.section .rodata
.org 0x0
.word    .Lt_0_2
.word    27
.word    55
.word    1024
.word    23
.word    129
.word    256
.word    4
.word    24
.word    8
.word    36
.word    20
.word    16
.word    &func1
.word    &func2
.word    &func3
.word    &func4
.word    &func5
.word    &func6
```

Difference items, types, and classes: encoding and decoding for LUT

```
.Lt_10_13:
    r17=loaduh(r30+#-584)
    r17=or(r17,#16)
    r17=extract(r17,#10,#6)
    storeh(r30+#-584)=r17
    r9=loaduh(r29+#16)
    r10=loadw(r29+#600)
    jump .Lt_10_294

.Lt_10_12:
    r20=loaduh(r30+#-584)
    r20=or(r20,#8)
    r20=extract(r20,#12,#6)
    storeh(r30+#-584)=r20
    r9=loaduh(r29+#16)
    r10=loadw(r29+#680)
    jump .Lt_10_294
```

```
.Lt_10_11:
    r21=loaduh(r30+#-584)
    r21=or(r21,#4)
    r21=extract(r21,#14,#6)
    storeh(r30+#-584)=r21
    r9=loaduh(r29+#16)
    r10=loadw(r29+#720)
    jump .Lt_10_294
```

DIFFERENCE CLASS

Difference Item1: Constant Operand

- Difference Type 1: constant operand in "logical-or operation"
- Difference Type 2: bit width in extract operation

Difference Item2: Memory Offset

- Difference Type 3: memory offsets in load word, i.e., loadw

EXAMPLE ENCODING:

Memory offset	Logical-or operand	Extract bit-width

31st bit — 15th bit — 7th bit — 0 bit

Example where encoding requires additional LUT

```
.Lt_30_1:
    r0=loadub(r25+#124)
    r1=#33
    r2=loadw(r24+#1020)
    r3=#125
    r4=#75
    r5=#85
    call Callee1
    jump .Lt_30_2
```

```
.Lt_30_3:
    r0=loadub(r25+#248)
    r1=#66
    r2=loadw(r24+#2040)
    r3=#10
    r4=#95
    r5=#51
    call Callee2
    jump .Lt_30_2
```

```
.Lt_30_7:
    r0=loadub(r25+#492)
    r1=#55
    r2=loadw(r24+#4088)
    r3=#114
    r4=#15
    r5=#49
    call Callee3
    jump .Lt_30_2
```

Difference Class

Item: Constant Operands
- Types: constants loaded in r1, r3, r4, r5

Item: Memory Offset
- Types: memory offsets for loadub and loadw

Item: function with same signature
- Types: the function called

EXAMPLE ENCODING REQUIRES AT LEAST THREE WORDS (12 bytes):

Constant for "r5"	Constant for "r4"	Constant for "r3"	Constant for "r1"

31st bit | 23rd bit | 15th bit | 7th bit | 0 bit

unused	offset for "loadw to r2"	offset for "loadub to r0"

31st bit | 24th bit | 9th bit | 0 bit

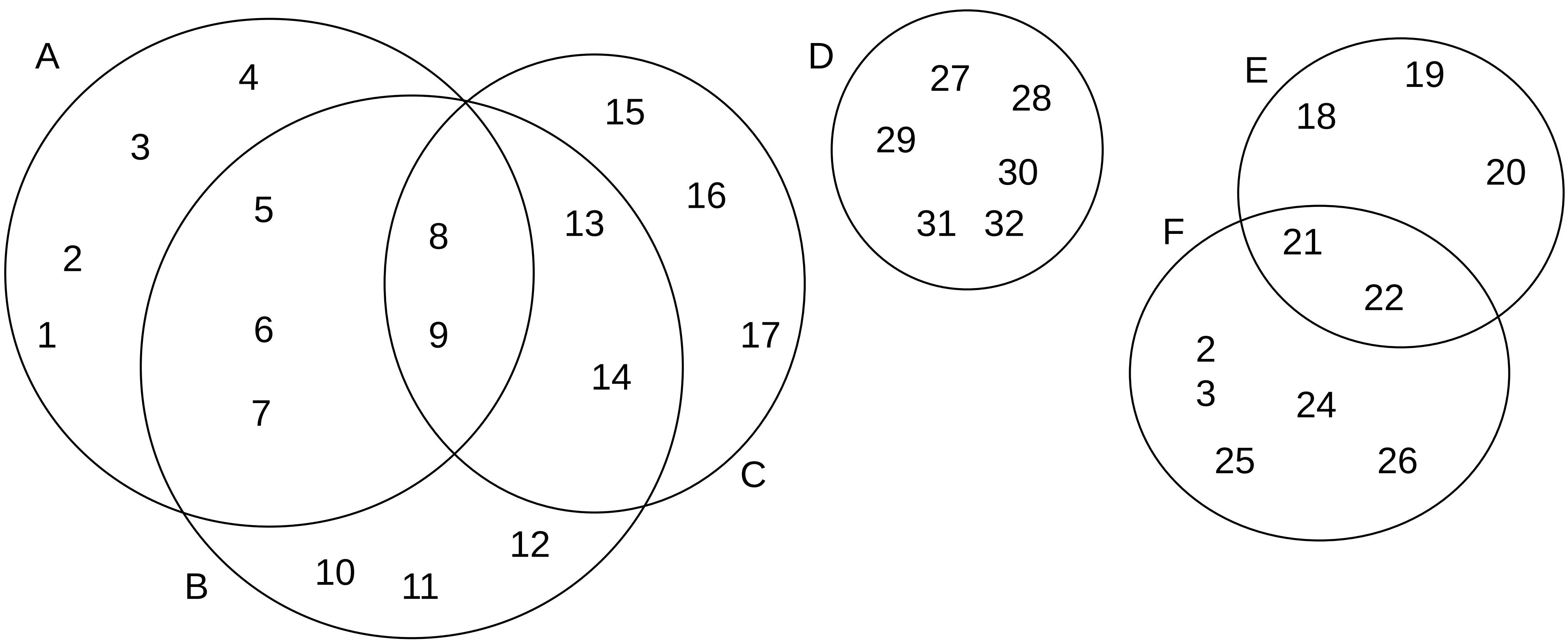
Callee Function Address

31st bit | 0 bit

Highlights of difference classification algorithm

- Input is pair of code regions for detecting similarity
  - Detected hierarchically: control flow graph → basic blocks → individual operations → operands
  - TN's (operands)
    - Globals
    - Locals – use-def chains determined and compared
  - Differences detected at operands, functions with same signature called
- A list of pair-wise code regions is formed, arranged in descending order of "the number of difference types in difference class of pair"
- Code regions having the same difference class clustered together
  - All code regions in a cluster can be replaced by single representative
- Code regions that belong to a difference class that is a subset of another difference class can sometimes be clustered together (if possible and profitable)
- Opportunities exist to improve the algorithm

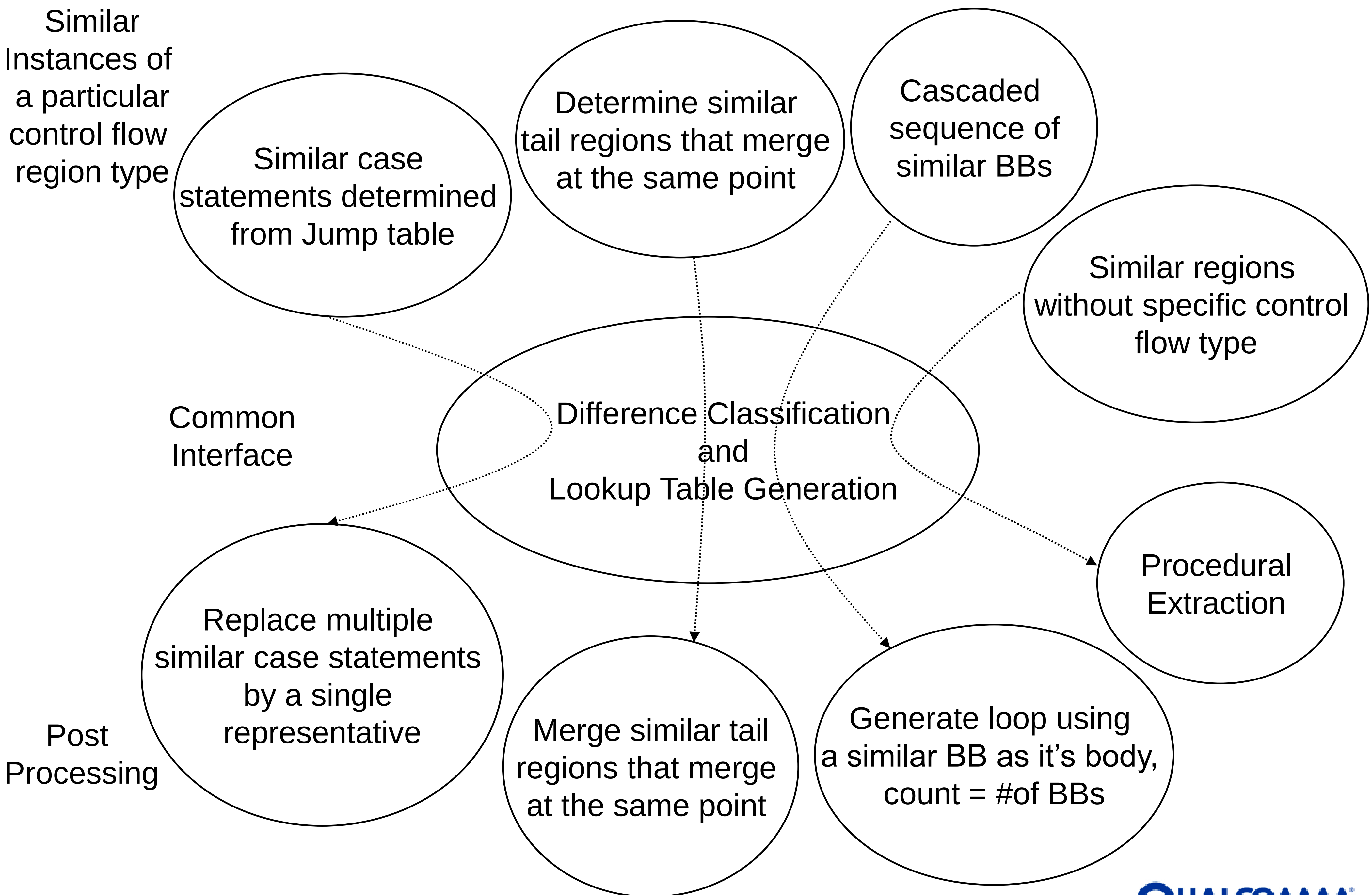
Venn diagram representation of difference classification and LUT generation



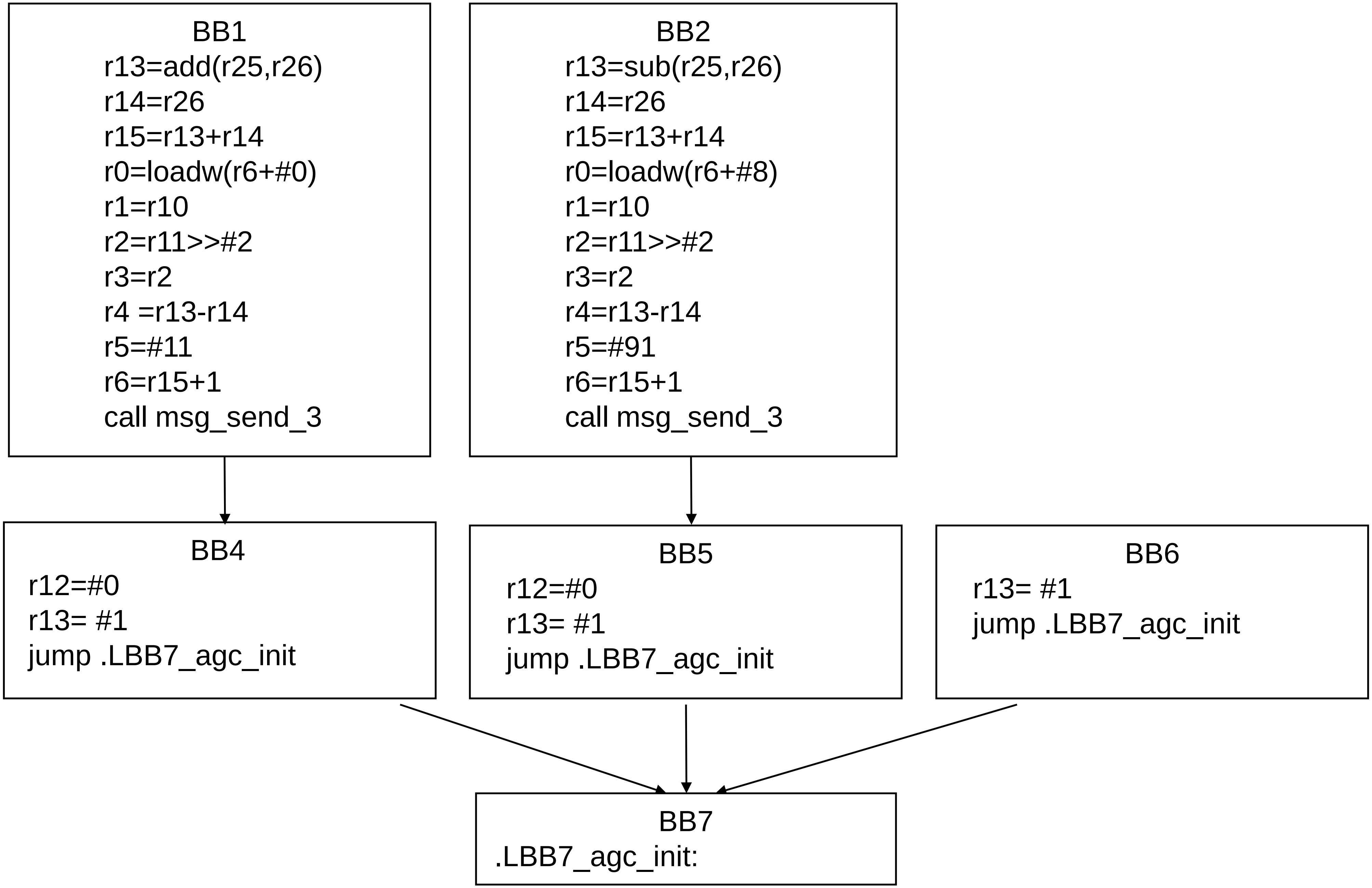
- {1,2,3,…..30,31,32} indicate code regions that are compared
- A, B, C, D, E, F indicate "difference type"
- Each distinct region indicates "difference class"

{1,2,3,4}, {5,6,7}, {8,9},….,{27,28,29,30,31,32}

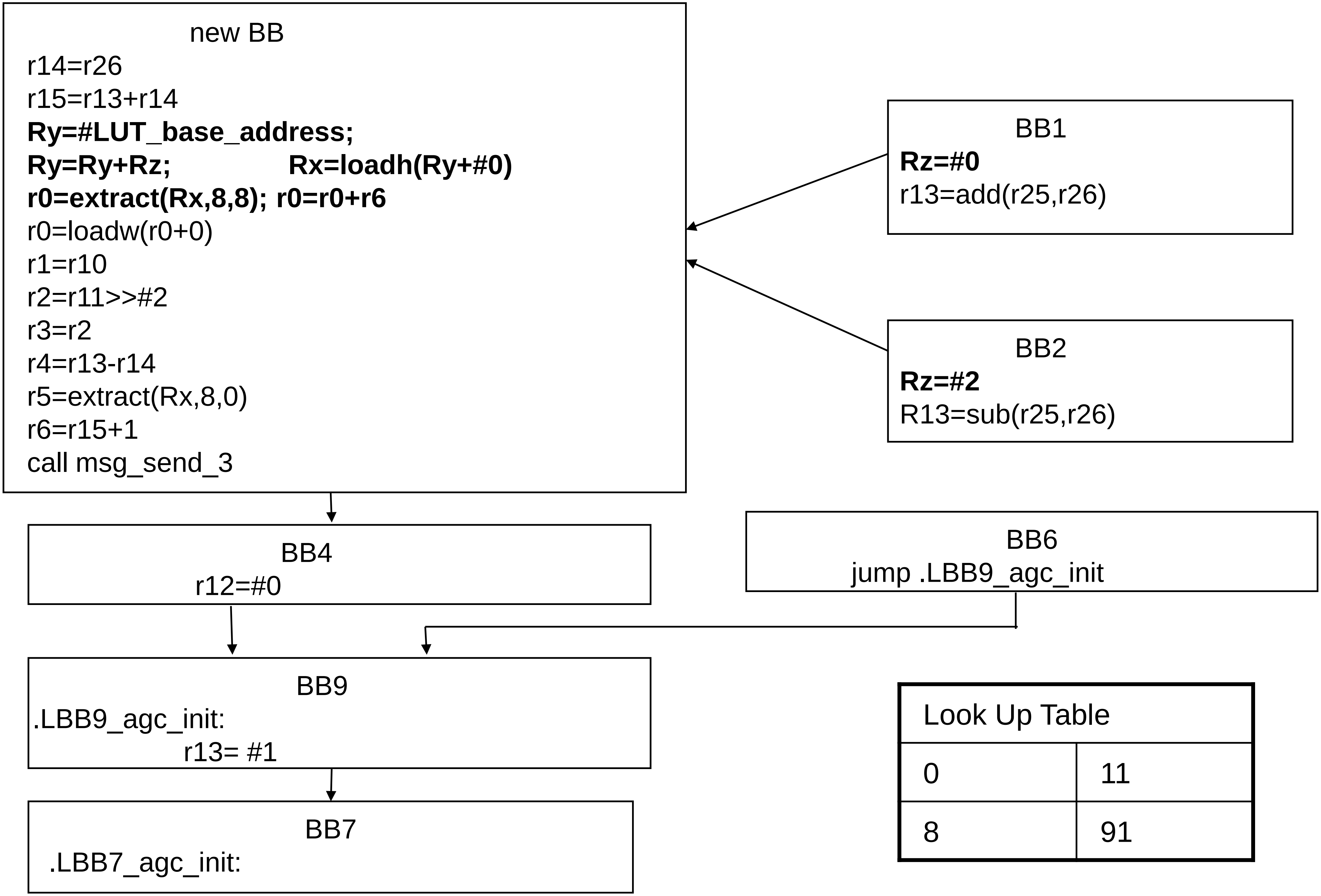
Overall framework



Tail merging example



Tail merging with differences in LUT



Look Up Table	
0	11
8	91

Cascaded regions replaced by loop with differences in LUT

```
BB1
r0=loadw(r6+#0)
r1=r10
r2=#106
r3=r11
call msg_send_3
```

```
BB2
r0=loadw(r6+#48)
r1=r10
r2=#135
r3=r11
call msg_send_3
```

```
BB3
r0=loadw(r6+#36)
r1=r10
r2=#224
r3=r11
call msg_send_3
```

```
BB4
r0=loadw(r6+#64)
r1=r10
r2=#298
r3=r11
call msg_send_3
```

```
BB5
r0=loadw(r6+#72)
r1=r10
r2=#234
r3=r11
call msg_send_3
```

New BB 6: **Ry = #LUT_base_address**
LoopCounter=#5

```
New BB 7
LoopStart:
        Rx=loadw(Ry++)
        Rz=extract(Rx,16,16)
        Rz=r6+Rz;
        r0=loadw(Rz);
        r1=r10
        r2=extract(Rx,16,0)
        r3=r11
        call msg_send_3
LoopEnd
```

LOOK UP TABLE:
Upper half-word is for load offset
Lower half-word is for constant loaded in r2

0	106
48	135
36	224
64	298
72	234

Procedural abstraction with differences in LUT

```
r4=add(r5,#10)
r4=mul(r4,r3)
r4=r4<<2;
r4=and(r4, r2)
r4=loadw(r4)
r4=or(r4,#12)

<OTHER
INSTRUCTIONS
EXACTLY SAME>
```

```
r0=#10
r1=#12

r4=add(r5,r0)
r4=mul(r4,r3)
r4=r4<<2;
r4=and(r4, r2)
r4=loadw(r4)
r4=or(r4,r1)

<OTHER
INSTRUCTIONS
EXACTLY SAME>
```

```
r0=#0
call NewProcedure
```

```
r4=add(r5,#14)
r4=mul(r4,r3)
r4=r4<<2;
r4=and(r4, r2)
r4=loadw(r4)
r4=or(r4,#51)

<OTHER
INSTRUCTIONS
EXACTLY SAME>
```

```
r0=#14
r1=#51

r4=add(r5,r0)
r4=mul(r4,r3)
r4=r4<<2;
r4=and(r4, r2)
r4=loadw(r4)
r4=or(r4,r1)

<OTHER
INSTRUCTIONS
EXACTLY SAME>
```

```
r0=#4
call NewProcedure
```

```
NewProcedure:

Rx=
  #LUT_base_address

Rx=Rx+r0
r0=loadw(Rx+#0)
r0=extract(r0 ,#8,#0)
r1=extract(r0 ,#8,#8)

r4=add(r5,r0)
r4=mul(r4,r3)
r4=r4<<2;
r4=and(r4, r2)
r4=loadw(r4)
r4=or(r4,r1)

<OTHER
INSTRUCTIONS
EXACTLY SAME>

RETURN
```

Look Up Table	
12	10
51	14

Code size comparison: Open64 and GCC (-Os)

Test cases are some of the functions in software for mobile device – networking protocol, modem, etc.

Test cases	GCC 4.3.2 (size in bytes)			GCC 3.4.6 (size in bytes)			Original Open64 (size in bytes)			Methodology in Open64 (size in bytes)		
	Pure text	rodata	**Total text**	Pure text	rodata	**Total text**	Pure text	rodata	**Total text**	Pure text	rodata	**Total text**
1	3368	6164	**9532**	3364	6164	**9528**	4040	7512	**11552**	1676	6568	**8244**
2	1152	308	**1460**	1224	312	**1536**	1352	352	**1704**	916	476	**1392**
3	1032	352	**1384**	1036	352	**1388**	1336	352	**1688**	572	416	**988**
4	896	0	**896**	876	0	**876**	1352	0	**1352**	116	224	**340**
5	2204	9204	**11408**	2204	9204	**11408**	2220	9208	**11428**	524	9208	**9732**
6	1052	1128	**2180**	1088	1128	**2216**	728	1952	**2680**	724	1392	**2116**

- *30% to 80% improvement for pure text (instructions only),*
- *5% to 60% improvement for total text (instructions and read only data)*

Code size and performance impact: Open64 (-Os)

Test	Original Open64		Methodology in Open64		Percentage improvement	
	Total text size	Kilo cycles	Total text size	Kilo cycles	**Total text size**	**Cycle Performance impact**
7	1884	3.89	1168	2.76	**+38**	**+27**
8	2448	34.1	1896	39.0	**+22**	**-14.3**
9	3744	1161	3672	1162	**+2**	**-0.09**
10	11860	17358	8372	17360	**+29**	**-0.05**
11	7392	20996	4580	21329	**+38**	**-1.5**

- *Code size always improves*
- *Slight degradation in performance: can be blindly used for non-time critical portions of code*

Other code size improvement efforts

- Register promotion of small structures (and members in big structures) to reduce unwanted loads/stores
- Better heuristics for unrolling (which estimate cycle benefit for unroll factor, and prevent unnecessary unrolling)
- Use –Os –ipa for code size optimization
- Better clustering of VHO switch lowering
- Generalized tail merging
- Recognizing loops out of straight line code

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