Compilers Design and Implementation

Data-Flow Analysis

Live-Variable Analysis

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Live-Variable Analysis

• What is Live-Variable Analysis?

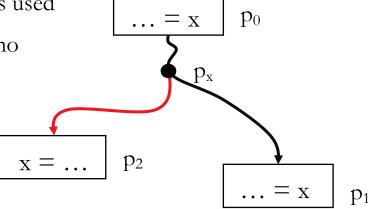
- For each Variable x where is the last program point p where the a specific value of x is used.
- In other words, for x and program point p determine if the value of x at p can still be used along some path starting at p.
 - If so, x is live at p
 - If not x is dead at p
- Must take Control-Flow into account : a Data-Flow Problem !!!

• Applications:

- Register Allocation: If a variable is dead at a given point p
 - Can reuse its storage, *i.e,* the register it occupies if any;
 - If its value as been modified must save the value to storage unless it is not live on exit of the procedure or loop

Live-Variable Analysis: Illustration

- At point p_0 the x variable is live:
 - There is a path to p_1 where value at p_0 is used
 - Beyond p_x towards p₂ the value of x is no longer needed and is dead



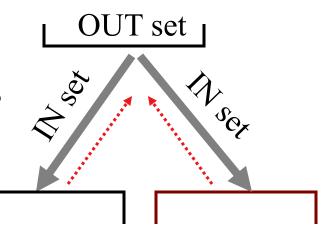
- Need to observe for each variable and for each program point:
 - Where is the last program point beyond which the value is not used
 - Trace back from uses to definitions and observe the first definition (backwards) that reaches that use.
 - That definition kills all uses backwards of it.

Data-Flow Analysis Formulation

- Variable is *live* at a point *p* if its value is used along *at least one*Path
 - A use of x prior to any definition in basic block means x must be alive
 - A definition of x in B prior to any subsequent use means previous uses must be dead
- Gen Set: Set of Variables Used in B
 - Upward Exposed Reads of B
- Kill Set: Set of Variables Defined in B

$$OUT(B) = \bigcup_{S \text{ a successor of } B} IN(s)$$

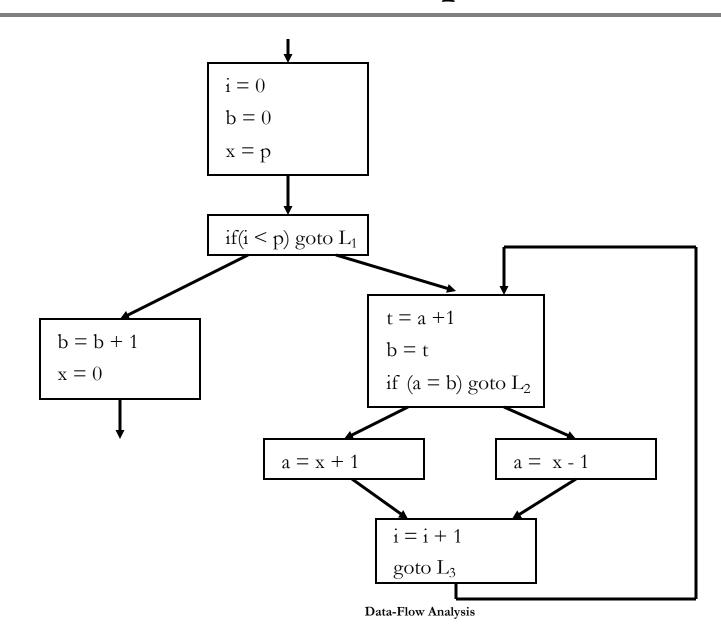
 $IN(B) = Use(B) \cup (OUT(B) - Def(B))$

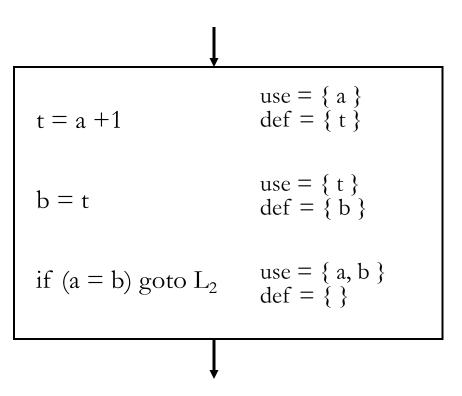


Data-Flow Analysis Formulation

- Initialize IN(B) to Empty Set
- Compute Gen/Use and Kill/Def for each Basic Block
 - Tracing backwards from end of block to beginning of block
 - Initialize Last Instruction's Out(i) to Empty
 - Use $IN(i) = use(i) \cup (OUT(i) def(i))$
- Iteratively Apply Relations to Basic Block Until Convergence

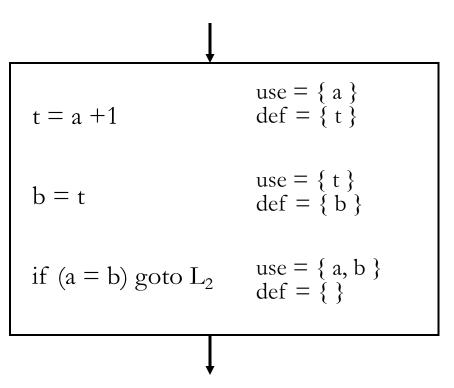
 - OUT(B) = U IN(s)
 IN(B) = Use(B) U (OUT(B) Def(B))
- Given OUT(B) use relations at instruction level to determine the live variables after each instruction





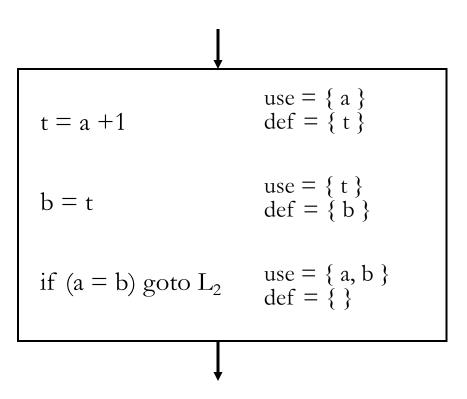
$$In = Use \cup (Out - Def)$$

$$In(i) = Use(i) \cup (Out(i) - Def(i))$$



In =
$$\{a,b\} \cup (\{\} - \{\}) = \{a,b\}$$

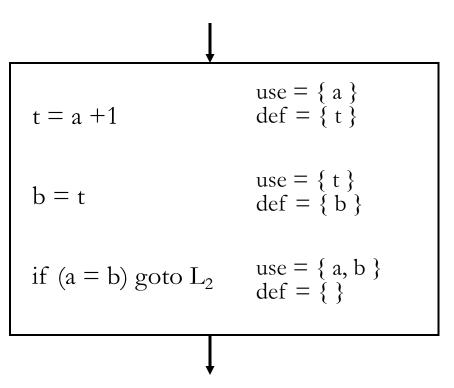
$$In(i) = Use(i) \cup (Out(i) - Def(i))$$



$$In = Use \cup (Out - Def)$$

$$Out = \{a,b\}$$

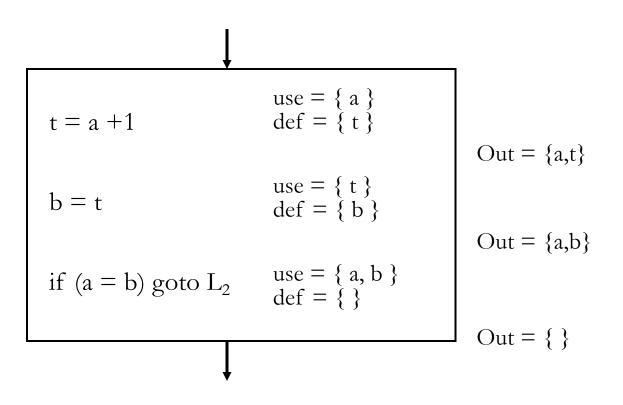
$$In(i) = Use(i) \cup (Out(i) - Def(i))$$



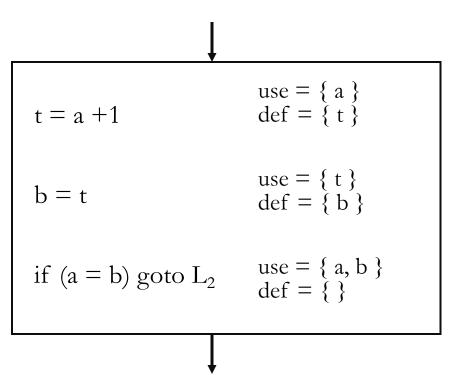
In =
$$\{t\} \cup (\{a,b\} - \{b\})$$

$$Out = \{a,b\}$$

$$In(i) = Use(i) \cup (Out(i) - Def(i))$$



$$In(i) = Use(i) \cup (Out(i) - Def(i))$$

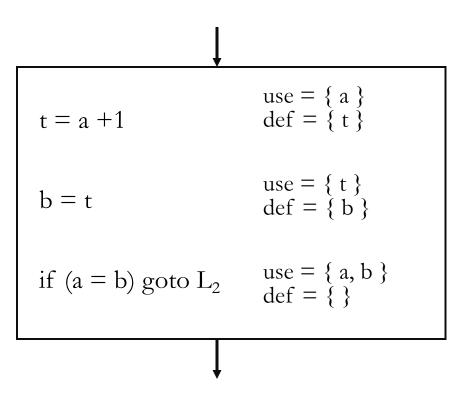


$$In = Use \cup (Out - Def)$$

Out =
$$\{a,t\}$$

Out =
$$\{a,b\}$$

$$In(i) = Use(i) \cup (Out(i) - Def(i))$$

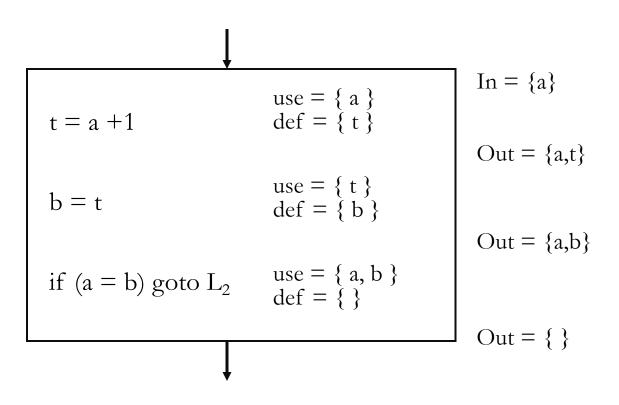


In =
$$\{a\} \cup (\{a,t\} - \{t\})$$

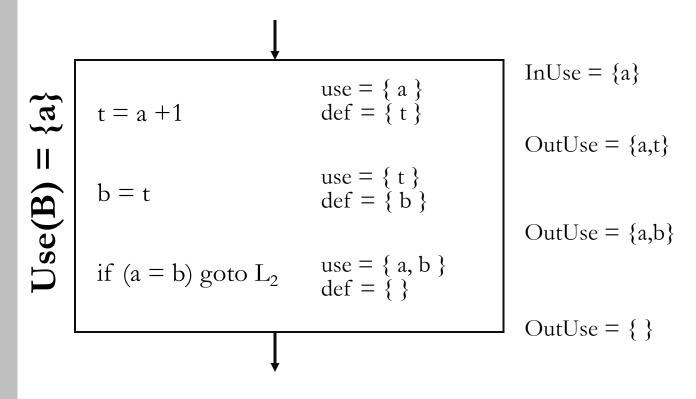
$$Out = \{a,t\}$$

Out =
$$\{a,b\}$$

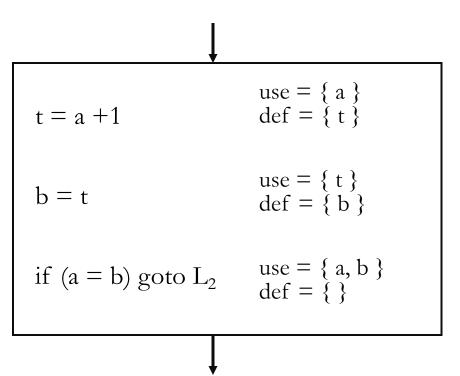
$$In(i) = Use(i) \cup (Out(i) - Def(i))$$



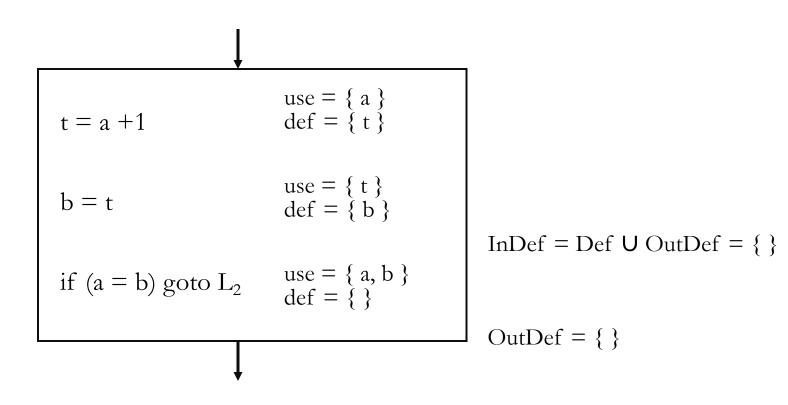
 $In(i) = Use(i) \cup (Out(i) - Def(i))$

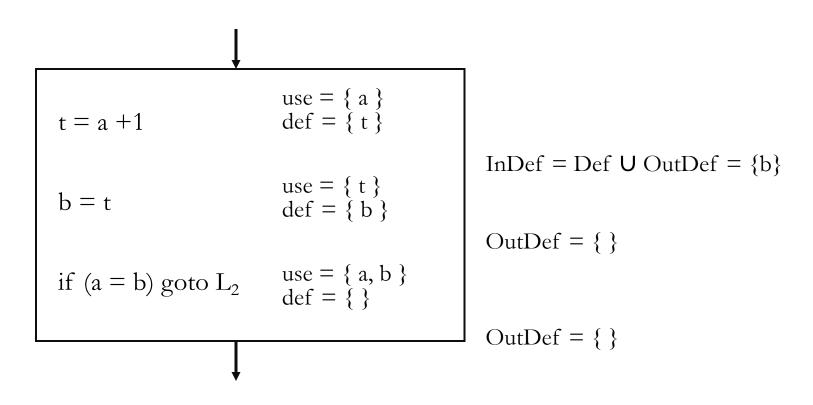


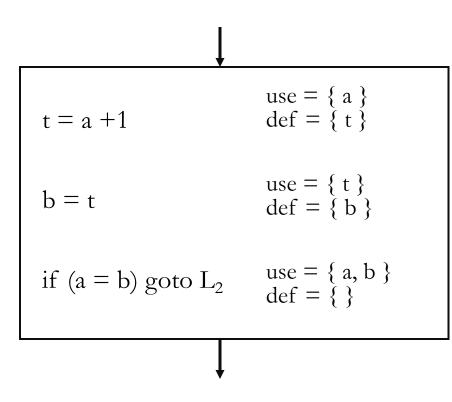
 $InUse(i) = Use(i) \cup (OutUse(i) - Def(i))$



OutDef = { }





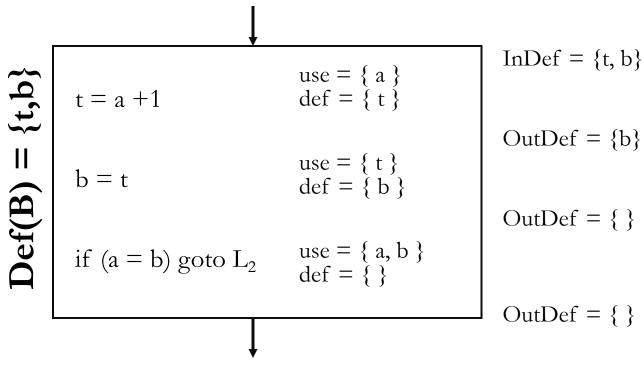


 $InDef = Def \ UOutDef = \{t\} \ U \ \{b\}$

OutDef = $\{b\}$

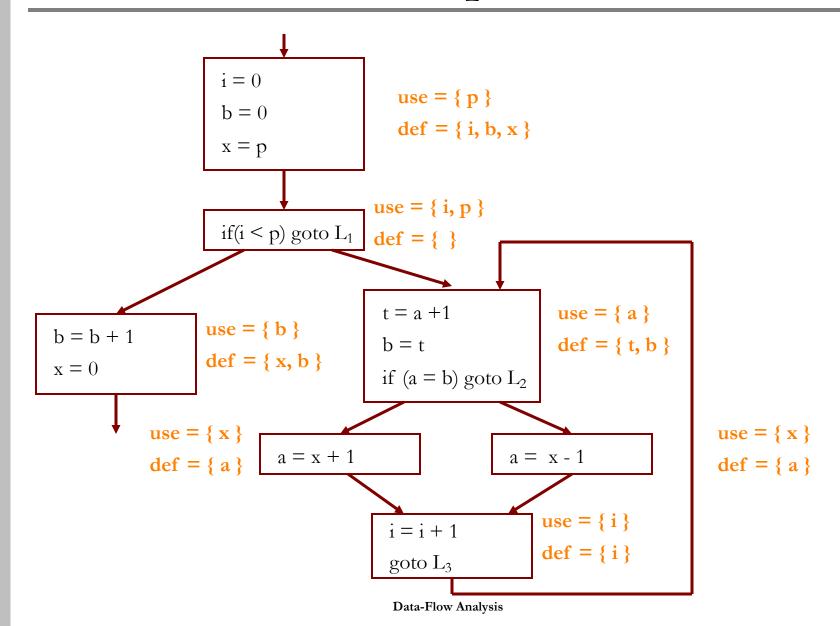
 $OutDef = \{ \}$

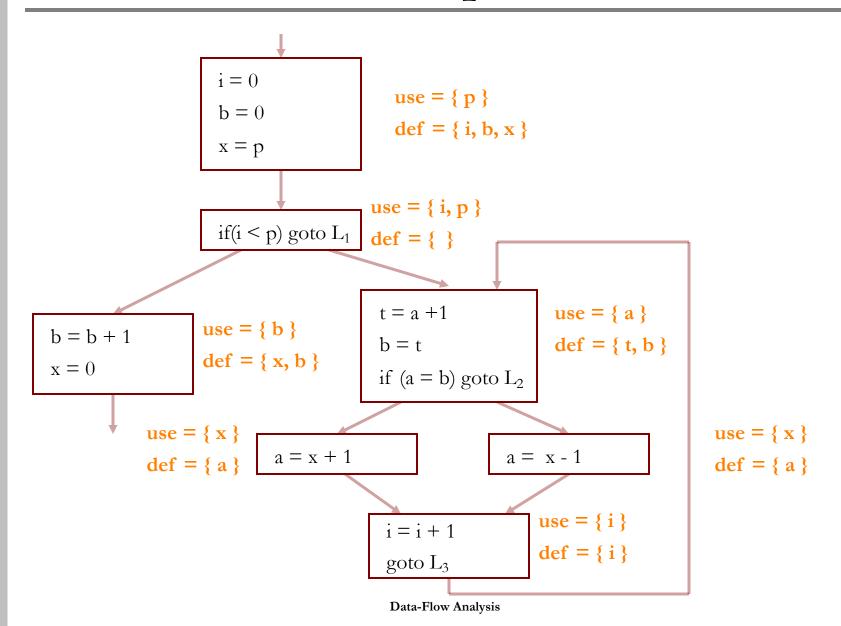
 $OutDef = \{ \}$



- Can be Accomplished by a Forward Scanning of the Block
 - Keep Track of Which Variables are Read before they are written thus computing the Upwards Exposed Reads (UpExp) or Use Function
 - Track Variables that are Written or Killed (VarKill) or Def Function

```
// Assume instruction in format "x \leftarrow y \text{ op } z"
for i \leftarrow 1 to Num Instructions in B do
   if (instr(i) is leader of B) then
      b \leftarrow Number(B);
      UpExp(b) \leftarrow \emptyset;
       VarKill(b) \leftarrow \emptyset;
   if y ∉ VarKill(b) then
       UpExp(b) \leftarrow UpExp(b) \cup \{y\}
   if z \notin VarKill(b) then
       UpExp(b) \leftarrow UpExp(b) \cup \{z\}
   VarKill(b) \leftarrow VarKill(b) \cup \{x\}
```





```
In = \{ \}
                           i = 0
                                                  use = \{p\}
                                                  def = \{ i, b, x \}
                           x = p
                      Out = { }
                                               use = \{i, p\}
                           if(i \le p) goto L_1
                                               def = { }
                           Out = { }
                                                   In = \{\}
In = \{ \}
                                                t = a + 1
                                                                       use = \{a\}
                         use = { b }
      b = b + 1
                                                b = t
                                                                      def = \{ t, b \}
                         def = \{x, b\}
      \mathbf{x} = 0
                                                if (a = b) goto L_2
Out = { }
                                                                     In = \{ \}
                                                    Out = { }
                                 In = \{ \}
                  use = \{x\}
                                                                                          use = \{x\}
                                                                a = x - 1
                                 a = x + 1
                  def = \{a\}
                                                                                          def = \{a\}
                                  Out = { }
                                                                      Out = \{\}
                                                  In = \{ \}
                                                                     use = \{i\}
                                                 i = i + 1
                                                                     def = \{i\}
                                                 goto L<sub>3</sub>
                                                 Data-Ftow Analysis
```

```
In = \{ \}
                                                                       OUT(B) = \cup IN(s)
                           i = 0
                                                  use = \{ p \}
                                                                              S a successor of B
                                                  def = \{ i, b, x \}
                                                                       IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = { }
                                               use = \{i, p\}
                           if(i \le p) goto L_1
                                               def = { }
                           Out = { }
                                                   In = \{\}
In = \{b\}
                                                t = a + 1
                                                                       use = \{a\}
                         use = { b }
      b = b + 1
                                                                      def = \{ t, b \}
                                                b = t
                         def = \{x, b\}
      \mathbf{x} = 0
                                                if (a = b) goto L_2
Out = { }
                                                                     In = \{ \}
                                 In = \{ \}
                                                    Out = \{\}
                                                                                            use = \{x\}
                  use = \{x\}
                                a = x + 1
                                                                a = x - 1
                  def = \{a\}
                                                                                            def = \{a\}
                                 Out = { }
                                                  In = \{\}
                                                                      Out = \{\}
                                                                     use = \{i\}
                                                 i = i + 1
                                                                     def = \{i\}
                                                 goto L<sub>3</sub>
                                                 Data-Ftow Analysis
```

```
In = \{ \}
                                                                      OUT(B) = UIN(s)
                           i = 0
                                                  use = \{ p \}
                                                                              S a successor of B
                                                  def = \{ i, b, x \}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{i, p, b\}
                                              use = \{i, p\}
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                                              def = { }
                           Out = \{b\}
                                                   In = \{\}
In = \{b\}
                                               t = a + 1
                                                                      use = \{a\}
                         use = { b }
      b = b + 1
                                                                      def = \{ t, b \}
                                                b = t
                         def = \{x, b\}
     \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                                                                     In = \{ \}
                                 In = \{ \}
                                                    Out = \{\}
                                                                                           use = \{x\}
                  use = \{x\}
                                a = x + 1
                                                                a = x - 1
                  def = \{a\}
                                                                                           def = \{a\}
                                 Out = { }
                                                  In = \{\}
                                                                     Out = { }
                                                                    use = \{i\}
                                                i = i + 1
                                                                    def = \{i\}
                                                 goto L<sub>3</sub>
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In = \{p\}
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                                                                             S a successor of B
                                                 def = \{ i, b, x \}
                                                                     IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{i, p, b\}
                                              use = \{i, p\}
                          if(i < p) goto L_1
                                              def = { }
                           Out = \{b\}
                                                  In = \{\}
In = \{b\}
                                               t = a + 1
                                                                     use = \{a\}
                         use = { b }
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                                                                     def = \{t, b\}
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                                               if (a = b) goto L_2
Out = { }
                                                                    In = \{ \}
                                 In = \{ \}
                                                   Out = \{\}
                  use = \{x\}
                                                                                          use = \{x\}
                                                               a = x - 1
                               a = x + 1
                  def = \{a\}
                                                                                          def = \{a\}
                                 Out = { }
                                                 In = \{ \}
                                                                    Out = \{\}
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                                                                    In = \{ \}
                                 In = \{ \}
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                                                                                          use = \{x\}
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                                                               a = x - 1
                  def = \{a\}
                                                                                          def = \{a\}
                                 Out = \{i\}
                                                In = \{i\}
                                                                    Out = \{i\}
                                                                   use = \{i\}
                                               i = i + 1
                                                                   def = \{i\}
                                                goto L<sub>3</sub>
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In = \{ p \} \downarrow
                                                                        OUT(B) = \cup IN(s)
                           i = 0
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                                                                               S a successor of B
                                                  def = \{ i, b, x \}
                                                                       IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{i, p, b\}
                                               use = \{i, p\}
                           if(i < p) goto L_1
                                               def = { }
                            Out = \{b\}
                                                    In = \{\}
In = \{b\}
                                                t = a + 1
                                                                       use = \{a\}
                          use = { b }
      b = b + 1
                                                                       def = \{t, b\}
                                                 b = t
                         def = \{ x, b \}
      \mathbf{x} = 0
                                                if (a = b) goto L_2
Out = { }
                                                                      In = \{ \}
                                  In = \{x, i\}
                                                    Out = { }
                  use = \{x\}
                                                                                             use = \{x\}
                                                                 a = x - 1
                  def = \{a\}
                                                                                             def = \{a\}
                                  Out = \{i\} In = \{i\}
                                                                      Out = \{i\}
                                                                     use = \{i\}
                                                 i = i + 1
                                                                     def = \{i\}
                                                 goto L<sub>3</sub>
                                                  Data-Ftow Analysis
```

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In = \{ p \} \downarrow
                                                                       OUT(B) = \cup IN(s)
                           i = 0
                                                  use = \{p\}
                                                                               S a successor of B
                                                  def = \{ i, b, x \}
                                                                       IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{i, p, b\}
                                               use = \{i, p\}
                           if(i \le p) goto L_1
                                               def = { }
                            Out = \{b\}
                                                    In = \{\}
In = \{b\}
                                                t = a + 1
                                                                       use = \{a\}
                          use = { b }
      b = b + 1
                                                                       def = \{ t, b \}
                                                b = t
                         def = \{ x, b \}
      \mathbf{x} = 0
                                                if (a = b) goto L_2
Out = { }
                                                                      In = \{ x, i \}
                                  In = \{x, i\}
                                                    Out = { }
                  use = \{x\}
                                                                                             use = \{x\}
                                                                 a = x - 1
                                a = x + 1
                  def = \{a\}
                                                                                             def = \{a\}
                                  Out = \{i\} In = \{i\}
                                                                      Out = \{i\}
                                                                     use = \{i\}
                                                 i = i + 1
                                                                     def = \{i\}
                                                 goto L<sub>3</sub>
                                                  Data-Ftow Analysis
```

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In = \{ p \} \downarrow
                                                                       OUT(B) = \cup IN(s)
                           i = 0
                                                  use = \{ p \}
                                                                              S a successor of B
                                                  def = \{ i, b, x \}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{i, p, b\}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = { }
                           Out = \{b\}
                                                 In = \{ a, i, x \}
In = \{b\}
                                                t = a + 1
                                                                      use = \{a\}
                         use = { b }
      b = b + 1
                                                                     def = \{t, b\}
                         def = \{x, b\}
      \mathbf{x} = 0
                                                if (a = b) goto L_2
Out = { }
                                 In = \{x, i\} Out = \{x, i\} In = \{x, i\}
                  use = \{x\}
                                                                                            use = \{x\}
                  def = \{ a \} | a = x + 1
                                                                a = x - 1
                                                                                            def = \{a\}
                                 Out = \{i\} In = \{i\}
                                                                     Out = \{i\}
                                                                    use = \{i\}
                                                i = i + 1
                                                                    def = \{i\}
                                                 goto L<sub>3</sub>
                                                 Data-Ftow Analysis
```

```
In = \{ p \} \rfloor
                                                                      OUT(B) = \cup IN(s)
                                                 use = \{p\}
                                                                             S a successor of B
                                                 def = \{ i, b, x \}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{i, p, b\}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = \{ \}
                           Out = \{b\}
                                                In = \{ a, i, x \}
In = \{b\}
                                               t = a + 1
                                                                     use = \{a\}
                         use = { b }
      b = b + 1
                                               b = t
                                                                     def = \{ t, b \}
                         def = \{x, b\}
     \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                                 In = \{x, a\} Out = \{x, a\} In = \{x, a\}
                  use = \{x\}
                                                                                           use = \{x\}
                  def = \{ a \} | a = x + 1
                                                               a = x - 1
                                                                                           def = \{a\}
                                 Out = \{i\} In = \{a, i, x\} Out = \{i\}
                                                                    use = \{i\}
                                                i = i + 1
                                                                    def = \{i\}
                                                goto L<sub>3</sub>
                                                 Hara-Flow-Analysis 1, X
```

```
In = \{ p \} \rfloor
                                                                      OUT(B) = \cup IN(s)
                                                 use = \{p\}
                                                                              S a successor of B
                                                 def = \{i, b, x\}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{ i, p, b \}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = \{ \}
                           Out = \{b\}
                                                In = \{ a, i, x \}
In = \{b\}
                                               t = a + 1
                                                                      use = \{a\}
                         use = { b }
      b = b + 1
                                                                     def = \{t, b\}
                                                b = t
                         def = \{x, b\}
     \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                               In = \{i,x\}
                                                 Out = \{x, a\} In = \{i,x\}
                  use = \{x\}
                                                                                           use = \{x\}
                  def = \{ a \} | a = x + 1
                                                               a = x - 1
                                                                                           def = \{a\}
                              Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                    use = \{i\}
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                                                 Hara-Flow-Analysis 1, X
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In = \{ p \} \rfloor
                                                                       OUT(B) = \cup IN(s)
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                                                                              S a successor of B
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                           x = p
                      Out = \{ i, p, b \}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = \{ \}
                                                 In = \{ a, i, x \}
                           Out = \{b\}
In = \{b\}
                                                t = a + 1
                                                                      use = \{a\}
                         use = { b }
      b = b + 1
                                                b = t
                                                                      def = \{t, b\}
                         def = \{x, b\}
      \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                               In = \{i,x\}
                                                  Out = \{i,x\} In = \{i,x\}
                  use = \{x\}
                                                                                           use = \{x\}
                  def = \{ a \} | a = x + 1
                                                                a = x - 1
                                                                                            def = \{a\}
                              Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                    use = \{i\}
                                                i = i + 1
                                                                    def = \{i\}
                                                 goto L<sub>3</sub>
                                                 Data-Ftow-Aralysis, X }
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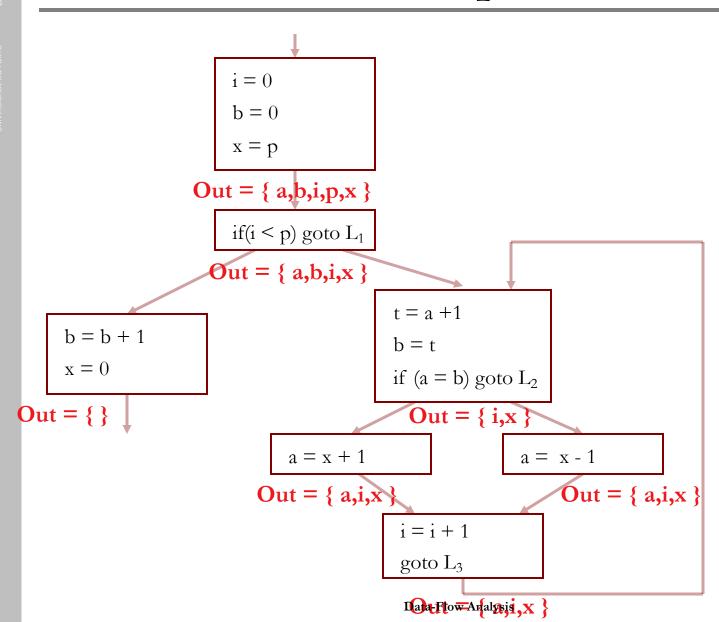
```
In = \{ p \} \rfloor
                                                                      OUT(B) = \cup IN(s)
                           i = 0
                                                 use = \{p\}
                                                                             S a successor of B
                                                 def = \{i, b, x\}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{ i, p, b \}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = { }
                           Out = \{b\}
                                                In = \{ a, i, x \}
In = \{b\}
                                               t = a + 1
                                                                     use = \{a\}
                         use = { b }
      b = b + 1
                                                                     def = \{t, b\}
                                               b = t
                         def = \{x, b\}
     \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                                                 Out = \{i,x\} In = \{i,x\}
                               In = \{i,x\}
                  use = \{x\}
                                                                                           use = \{x\}
                  def = \{ a \} | a = x + 1
                                                               a = x - 1
                                                                                           def = \{a\}
                              Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                    use = \{i\}
                                                i = i + 1
                                                                   def = \{i\}
                                                goto L<sub>3</sub>
                                                 Data-Ftow-Analysis, X
```

```
In = \{ p \} \rfloor
                                                                      OUT(B) = \cup IN(s)
                           i = 0
                                                  use = \{p\}
                                                                              S a successor of B
                                                 def = \{i, b, x\}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{ i, p, b \}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = \{ \}
                           Out = \{b\}
                                                In = \{ a, i, x \}
In = \{b\}
                                               t = a + 1
                                                                      use = \{a\}
                         use = { b }
      b = b + 1
                                                                     def = \{t, b\}
                                                b = t
                         def = \{x, b\}
     \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                                                 Out = \{i,x\} In = \{i,x\}
                               In = \{i,x\}
                  use = \{x\}
                                                                                           use = \{x\}
                  def = \{ a \}  a = x + 1
                                                                a = x - 1
                                                                                           def = \{a\}
                              Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                    use = \{i\}
                                                i = i + 1
                                                                    def = \{i\}
                                                goto L<sub>3</sub>
                                                 Data-Ftow-Analysis, X
```

```
In = \{ p \} \rfloor
                                                                       OUT(B) = \cup IN(s)
                           i = 0
                                                  use = \{p\}
                                                                              S a successor of B
                                                  def = \{ i, b, x \}
                                                                      IN(B) = Use(B) \cup (OUT(B) - Def(B))
                           x = p
                      Out = \{ i, p, b \}
                                              use = \{i, p\}
                           if(i < p) goto L_1
                                              def = \{ \}
                                                In = \{ a, i, x \}
                           Out = \{b\}
In = \{b\}
                                               t = a + 1
                                                                      use = \{a\}
                         use = { b }
      b = b + 1
                                                b = t
                                                                     def = \{t, b\}
                         def = \{x, b\}
     \mathbf{x} = 0
                                               if (a = b) goto L_2
Out = { }
                               In = \{i,x\}
                                                  Out = \{i,x\} In = \{i,x\}
                  use = \{x\}
                                                                                           use = \{x\}
                  def = \{ a \} | a = x + 1
                                                                a = x - 1
                                                                                           def = \{a\}
                              Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                    use = \{i\}
                                                i = i + 1
                                                                    def = \{i\}
                                                goto L<sub>3</sub>
                                                 Data-Ftow-Analysis, X
```

```
In = \{ p \} \rfloor
                                                                     OUT(B) = UIN(s)
                                                 use = \{p\}
                                                                            S a successor of B
                                                def = \{i, b, x\}
                                                                     IN(B) = Use(B) \cup (OUT(B) - Def(B))
                          x = p
                      Out = \{a,b,i,p,x\}
                          if(i < p) goto L_1
                                             def = { }
                        Out = \{a,b,i,x\}
                                              In = \{ a, i, x \}
In = \{b\}
                                               t = a + 1
                                                                    use = \{a\}
                         use = { b }
      b = b + 1
                                               b = t
                                                                    def = \{ t, b \}
                        def = \{x, b\}
     \mathbf{x} = 0
                                              if (a = b) goto L_2
Out = { }
                              In = \{i,x\}
                                                 Out = \{i,x\} In = \{i,x\}
                  use = \{x\}
                                                                                         use = \{x\}
                 def = \{ a \} | a = x + 1
                                                               a = x - 1
                                                                                          def = \{a\}
                              Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                   use = \{i\}
                                               i = i + 1
                                                                   def = \{i\}
                                                goto L<sub>3</sub>
                                                Data-Ftow-Analysis, X
                                                                                                          38
```

```
In = \{a, p\}
                                                                    OUT(B) = \cup IN(s)
                                                use = \{p\}
                                                                           S a successor of B
                                                def = \{i, b, x\}
                                                                    IN(B) = Use(B) \cup (OUT(B) - Def(B))
                     Out = \{a,b,i,p,x\}
                          if(i < p) goto L_1
                                             def = { }
                        Out = \{a,b,i,x\}
                                              In = \{ a, i, x \}
In = \{b\}
                                              t = a + 1
                                                                    use = \{a\}
                        use = { b }
     b = b + 1
                                              b = t
                                                                   def = \{t, b\}
                        def = \{ x, b \}
     \mathbf{x} = 0
                                              if (a = b) goto L_2
Out = { }
                                                Out = \{i,x\} In = \{i,x\}
                              In = \{i,x\}
                 use = \{x\}
                                                                                         use = \{x\}
                 def = \{ a \} | a = x + 1
                                                              a = x - 1
                                                                                         def = \{a\}
                             Out = \{a,i,x\} In = \{a,i,x\} Out = \{a,i,x\}
                                                                  use = \{i\}
                                               i = i + 1
                                                                  def = \{i\}
                                               goto L<sub>3</sub>
                                               Data-Ftow-Analysis, X
```



Summary

- What is Live-Variable Analysis?
 - Backward Data-Flow Analysis Problem
 - Upwards-Exposed (Gen): Forward Pass computation

- Most Significant Application
 - Register Allocation