Arithmetic Coding

Let \( v = 0.\)"codeword"
Last Lecture: Variable-Length Codes

Fundamental Lossless Coding Theorem

- Entropy rate as greatest lower bound for lossless coding

\[
\bar{\ell} \geq \bar{H}(X) = \lim_{N \to \infty} \frac{H_N(X)}{N} \quad \text{with} \quad H_N(X) = \mathbb{E}\left\{ -\log_2 p(X_k, X_{k+1}, \ldots, X_{k+N-1}) \right\}
\]

Variable-Length Codes

- Scalar codes: Individual codeword for each alphabet letter
- Conditional codes: Switching of codeword tables depending on a condition
- Block codes: One codeword for block of \( N > 1 \) symbols
- V2V codes: Codewords for variable-length symbol sequences

\[ \rightarrow \] Huffman algorithm yields optimal prefix code for each type of codes

!!! Block Huffman codes for large \( N \) yield coding efficiency very close to entropy rate

(\text{but cannot implemented due to extreme memory requirements for storing codeword table})
Motivation

- Block codes for large $N$ stay efficient even if they are slightly suboptimal
  \[
  \left( \frac{1}{N} H_N \right) + \left( \frac{A}{N} \right) \leq \bar{\ell} < \left( \frac{1}{N} H_N \right) + \left( \frac{1+ A}{N} \right) \quad \text{with} \quad A \ll N
  \]

- Realize encoding and decoding without storing a codeword table

Shannon-Fano-Elias Coding

- Idea: Code message by transmitting one value inside a probability interval of the cdf

- Require $K = \lceil - \log_2 p(\cdots) \rceil$ bits (same as for Shannon code)

Iterative Shannon-Fano-Elias Coding

- Probability interval can be determined by iterative refinement using simple models for conditional probabilities $p(a | \cdots)$ (e.g., iid model or Markov model)

- Enables iterative encoding and decoding with reasonably small pmfs
Given: Sequence $s = \{s_1, s_2, s_3, \cdots, s_N\}$ of $N$ symbols

1. Initialization of probability interval:
   \[ W_0 = 1 \quad \text{and} \quad L_0 = 0 \]

2. Iterative refinement (for $n = 1$ to $N$):
   \[ W_n = W_{n-1} \cdot p(s_n | \cdots) \]
   \[ L_n = L_{n-1} + W_{n-1} \cdot c(s_n | \cdots) \]

3. Determine codeword length and codeword value:
   \[ K = \lceil A - \log_2 W_N \rceil \quad (A = 0 \text{ or } 1) \]
   \[ z = \lceil L_N \cdot 2^K \rceil \]

4. Transmit codeword:
   - Binary representation of $z$ with $K$ bits
Review: Iterative Shannon-Fano-Elias Decoding Algorithm

Given:
- Codeword: integer $z$ with $K$ bits
- Number $N$ of symbols to be decoded
- Ordered alphabet $A = \{a_1, a_2, \cdots\}$

1. Initialization: $W_0 = 1$, $L_0 = 0$, $v = z \cdot 2^{-K}$

2. Iterative decoding (for $n = 1$ to $N$):
   a. Upper boundary $U_1$ for first symbol $a_1$ of $A$
      
      $k = 1$, $U_k = L_{n-1} + W_{n-1} \cdot p(a_k | \cdots)$

   b. While ($v \geq U_k$), proceed to next symbol of $A$
      
      $k = k + 1$, $U_k = U_{k-1} + W_{n-1} \cdot p(a_k | \cdots)$

   c. Output decoded symbol $s_n = a_k$

   d. Update interval:
      
      $W_n = W_{n-1} \cdot p(s_n | \cdots)$
      
      $L_n = U_k - W_n$
Implementation Aspects of Shannon-Fano-Elias Coding

Iterative Shannon-Fano-Elias Coding

- Iterative interval refinement
  - Very simple if we use simple models for conditional pmfs $p(a | \cdots)$
  - In practice: IID model or conditional model with small number of conditions

Question: Can we design a practical coding method based on Shannon-Fano-Elias coding?
Implementation Aspects of Shannon-Fano-Elias Coding

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- Iterative interval refinement
  - Very simple if we use simple models for conditional pmfs $p(a | \cdots)$
  - In practice: IID model or conditional model with small number of conditions
- Simple codeword construction
  - Straightforward concept for known interval boundaries

Can we implement it? No, not really (at least not for large $N$). Require arbitrarily high precision for real values $W, L_n, \text{and } v$. Standard floating-point values are not sufficient.
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Arithmetic Coding

Idea of Arithmetic Coding

- Fixed-precision approximation of Shannon-Fano-Elias coding
Arithmetic Coding

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- Represent pmf with standard integers (e.g., of 8, 16, or 32 bits)
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- Represent interval width and lower boundary with standard integers
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Realizations of Arithmetic Coding

- There are different variants
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- There are different variants
- Will discuss original approach by R. Pasco (1976, PhD thesis, Stanford)
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Realizations of Arithmetic Coding

- There are different variants
- Will discuss original approach by R. Pasco (1976, PhD thesis, Stanford)
- Other popular realizations
Quantization of PMF

Fixed-Precision Approximation of Probability Masses

- Represent probability masses $p(a)$ by $V$-bit integers $p_V(a)$

$$p(a) = p_V(a) \cdot 2^{-V} = 0.xxx \ldots x000 \ldots$$
Quantization of PMF

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\[
p(a) = p_V(a) \cdot 2^{-V} = 0.\underbrace{xxx \cdots x}_{V \text{ bits}}000 \cdots
\]

→ Resulting modified cmf $c(a)$ can also be represented by $V$-bit integers $c_V(a)$

\[
c(a) = \sum_{\forall b < a} p(b) = \left( \sum_{\forall b < a} p_V(b) \right) \cdot 2^{-V} = c_V(a) \cdot 2^{-V}
\]
Quantization of PMF

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- Represent probability masses $p(a)$ by $V$-bit integers $p_V(a)$

$$p(a) = p_V(a) \cdot 2^{-V} = 0.\overline{xxx \cdots x} 000 \cdots$$

$V$ bits

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Requirements on Pmf Approximation

- Probability masses must be non-zero and pmf must be valid

$$\forall a : p_V(a) > 0 \quad \text{and} \quad \sum_{\forall a} p_V(a) \leq 2^V$$
Quantization of Interval Width

Fixed-Precision Approximation of Interval Width

- Represent interval width $W_n$ by $U$-bit integers $A_n$ and counter $z_n$

\[ W_n = A_n \cdot 2^{-z_n} = 0.\overbrace{00000 \cdots 0}^{z_n \text{ bits}} \overbrace{1xxxx \cdots x}^{z_n-U \text{ bits}} \underbrace{000 \cdots}_{A_n (U \text{ bits})} \]

\{ very similar to representation of floating-point numbers in a computer \}
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- Use maximum possible precision for $A_n$

  $A_n$ should always have the form:
  $$A_n = \underbrace{1xxx \cdots x}_{U \text{ bits}}$$
  (binary representation)
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- Use maximum possible precision for $A_n$

  $\Rightarrow$ $A_n$ should always have the form: $A_n = \underbrace{1xxxx \cdots x}_{U \text{ bits}}$ (binary representation)

  $\Rightarrow$ That means, $A_n$ is restricted to: $2^{U-1} \leq A_n < 2^U$
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\text{very similar to representation of} \\
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\end{align*}

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  - $A_n$ should always have the form:
    $$A_n = \underbrace{1xxx \cdots x}_{U \text{ bits}}$$

  - That means, $A_n$ is restricted to:
    $$2^{U-1} \leq A_n < 2^U$$

  - Use following initialization:
    $$A_0 = 2^U - 1 \quad \iff \quad W_0 = 1 - 2^U = 0.\underbrace{1111 \cdots 1}_{U \text{ bits}}$$
    $$z_0 = U$$
Refinement of Interval Width

Conventional Refinement of Interval Width

\[ W_n = W_{n-1} \cdot p(s_n) \]

\[ A_n \cdot 2^{-z_n} = \left( A_{n-1} \cdot p_V(s_n) \right) \cdot 2^{-(z_{n-1}+V)} \]

\( (U+V) \)-bit integer

In general:

\( W_n - 1 \cdot p(s_n) \) cannot be represented using a \( U \)-bit integer

What can we do?

Requirement for Unique Decodability

Code remains uniquely decodable if we ensure:

\( 0 < W_n \leq W_{n-1} \cdot p(s_n) \)

Solution:

Rounding down of \( W_{n-1} \cdot p(s_n) \) in each iteration, so that \( W_n \) can be represented using \( A_n \cdot 2^{-z_n} \) with \( 2^{U-1} \leq A_n < 2^U \).
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⇒ Solution: Rounding down of \( W_{n-1} \cdot p(s_n) \) in each iteration, so that \( W_n \) can be represented using \( A_n \cdot 2^{-z_n} \) with \( 2^{U-1} \leq A_n < 2^U \)
Rounding of Interval Width in Iterative Interval Refinement

- Binary representations of interval width $W_{n-1}$ and probability mass $p(s_n)$

$W_{n-1} = A_{n-1} \cdot 2^{-z_{n-1}} \Rightarrow W_{n-1} = 0.\underbrace{00000\cdots0}_{z_{n-1}-U \text{ bits}} \underbrace{1xx\cdots x000\cdots}_{U \text{ bits}}$

$p(s_n) = p_V(s_n) \cdot 2^{-V} \Rightarrow p(s_n) = 0.\underbrace{xxx\cdots x000\cdots}_{V \text{ bits}}$
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W_{n-1} = A_{n-1} \cdot 2^{-z_{n-1}} \quad \Rightarrow \quad W_{n-1} = 0.00000 \cdots 01xx \cdots x000 \cdots
$$

$$
p(s_n) = p\nu(s_n) \cdot 2^{-V} \quad \Rightarrow \quad p(s_n) = 0.xxx \cdots x000 \cdots
$$

- Rounding in interval refinement $W_{n-1} \cdot p(s_n) \mapsto W_n$

$$
W_{n-1} \cdot p(s_n) = 0.00000 \cdots 000 \cdots
$$

$$
\quad \underbrace{00 \cdots 0}_{z_{n-1} - U \text{ bits}} \underbrace{1x \cdots x}_{U \text{ bits}} \underbrace{xx \cdots x}_{V - \Delta z \text{ bits}} 000 \cdots
$$

$$
\quad A_{n-1} \cdot p\nu(s_n)
$$
Rounding of Interval Width in Iterative Interval Refinement

- Binary representations of interval width $W_{n-1}$ and probability mass $p(s_n)$

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W_{n-1} = A_{n-1} \cdot 2^{-z_{n-1}} \quad \Rightarrow \quad W_{n-1} = 0.\overbrace{00000\cdots}^{z_{n-1}-U \text{ bits}} 01\overbrace{xx\cdots x}^{U \text{ bits}} 000\cdots
\]

\[
p(s_n) = p_V(s_n) \cdot 2^{-V} \quad \Rightarrow \quad p(s_n) = 0.\overbrace{xxx\cdots x}^{V \text{ bits}} 000\cdots
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W_{n-1} \cdot p(s_n) = 0.\overbrace{00000\cdots0}^{z_{n-1}-U \text{ bits}} \underbrace{00\cdots0}_{U \text{ bits}} \underbrace{1x\cdots x}_{V-\Delta z \text{ bits}} \underbrace{xx\cdots x}_{\Delta z \text{ bits}} 000\cdots
\]

\[
W_n = 0.\overbrace{00000\cdots0}^{z_{n-1}-U \text{ bits}} \underbrace{00\cdots0}_{U \text{ bits}} \underbrace{1x\cdots x}_{A_n} \underbrace{00\cdots0}_{A_{n-1} \cdot p_V(s_n)} 000\cdots
\]
Arithmetic Operations for Update of Interval Width

\[ W_{n-1} \cdot p(s_n) = 0.00000 \ldots 0 \begin{cases} \Delta z \text{ bits} \\ \begin{array}{c} z_{n-1} - U \text{ bits} \\ U + V \text{ bits: } A_{n-1} \cdot p_V(s_n) \end{array} \\ V - \Delta z \text{ bits} \end{cases} 000 \ldots \]

\[ W_n = 0.00000 \ldots 0 \begin{cases} \Delta z \text{ bits} \\ \begin{array}{c} z_{n-1} - U \text{ bits} \\ U \text{ bits} \end{array} \\ A_n \end{cases} 00 \ldots 0 000 \ldots \]

Update of interval width

1. Calculate intermediate \((U + V)\)-bit integer: \( A^*_n = A_{n-1} \cdot p_V(s_n) \)
Arithmetic Operations for Update of Interval Width

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\[ z_{n-1} \underbrace{-U \text{ bits}}_{\text{z}} \]

\[ W_{n} = 0.00000 \ldots 0 \underbrace{00 \ldots 0}_{\Delta z \text{ bits}} \underbrace{1x \ldots x}_{U \text{ bits}} \underbrace{00 \ldots 0 000 \ldots}_{A_n} \underbrace{00 \ldots 0}_{\text{z}} \underbrace{-U \text{ bits}}_{\text{z}} \]

Update of interval width

1. Calculate intermediate \((U+V)\)-bit integer: \(A_n^* = A_{n-1} \cdot p_V(s_n)\)
2. Determine number \(\Delta z\) of leading zeros in \((U+V)\)-bit integer \(A_n^*\) (check at most \(V\) bits)
### Arithmetic Operations for Update of Interval Width

\[ W_{n-1} \cdot p(s_n) = 0.00000\cdots0 \]

\[ z_{n-1-U} \text{ bits} \quad \Delta z \text{ bits} \quad U \text{ bits} \quad V - \Delta z \text{ bits} \]

\[ A_n^* = A_{n-1} \cdot p_V(s_n) \]

\[ W_n = 0.00000\cdots0 \quad 00\cdots0 \quad 1x\cdots x \quad xx\cdotsx \quad 000\cdots0 \]

\[ z_{n-U} \text{ bits} \quad \Delta z \text{ bits} \quad U \text{ bits} \]

#### Update of interval width

1. Calculate intermediate \((U+V)\)-bit integer: \[ A_n^* = A_{n-1} \cdot p_V(s_n) \]
2. Determine number \(\Delta z\) of leading zeros in \((U+V)\)-bit integer \(A_n^*\) (check at most \(V\) bits)
3. Update interval width according to:
   \[ A_n = (A_n^* \ll \Delta z) \gg V \]
   \(\ll\) and \(\gg\) = bit shifts to the left and to the right
   \[ z_n = z_{n-1} + \Delta z \]
   (note: \(z_n\) is not required for updating the interval width)
Intermediate Summary: Calculation of Interval Width

Representation of Interval Width and Probability Masses

\[ W_n = A_n \cdot 2^{-z_n} \]

with \( A_n \) being an \( U \)-bit integer with \( 2^{U-1} \leq A_n < 2^U \)

\[ p(s_n) = p_V(s_n) \cdot 2^{-V} \]

with \( p_V(s_n) \) being a \( V \)-bit integer with \( p_V(s_n) > 0 \) and \( \sum_{\forall a} p_V(a) \leq 2^V \)

Arithmetic Calculation of Interval Width

1. Initialization

\[ A_0 = (1 \ll U) - 1 \]

2. Update in each iteration

\[ A_n^* = A_{n-1} \cdot p_V(s_n) \]

\[ \Delta z = \text{number of leading zeros in } (U+V)\text{-bit integer } A_n^* \]

\[ A_n = (A_n^* \ll \Delta z) \gg V \]
Update of Lower Interval Boundary

- Remember: Conventional update

\[ L_n = L_{n-1} + W_{n-1} \cdot c(s_n) \]
Update of Lower Interval Boundary

- Remember: Conventional update
  \[ L_n = L_{n-1} + W_{n-1} \cdot c(s_n) \]

- Binary representations of interval width \( W_{n-1} \) and modified cmf \( c(s_n) \)

\[
W_{n-1} = A_{n-1} \cdot 2^{-z_{n-1}} \quad \rightarrow \quad W_{n-1} = 0.0000000\cdots01xxxx\cdotsx000\cdots
\]
\[
c(s_n) = c_V(s_n) \cdot 2^{-V} \quad \rightarrow \quad c(s_n) = 0.xxxxxx\cdots\cdot000\cdots
\]
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- Remember: Conventional update

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- Binary representations of interval width \( W_{n-1} \) and modified cmf \( c(s_n) \)

\[
\begin{align*}
W_{n-1} &= A_{n-1} \cdot 2^{-z_{n-1}} & \rightarrow & & W_{n-1} &= 0.0000000 \cdots 01xxxx \cdots x000 \cdots \\
c(s_n) &= c_V(s_n) \cdot 2^{-V} & \rightarrow & & c(s_n) &= 0.xxxxxx \cdots x000 \cdots \\
\end{align*}
\]

- Binary representation of product \( W_{n-1} \cdot c(s_n) \)

\[
W_{n-1} \cdot c(s_n) = 0.00000 \cdots 0xxxxxx \cdots x000 \cdots 
\]
Effect on Binary Representation of Lower Interval Boundary

\[ W_{n-1} \cdot c(s_n) = 0.\overline{00000\cdots0}^{z_{n-1}+V \text{ bits}} \overline{xxxxxx\cdots x}^{z_{n-1}-U \text{ bits}} \overline{000\cdots}^{A_{n-1}\cdot c_V(s_n) \text{ (}U+V\text{ bits)}} \]

What is the effect of an update \( L_n = L_{n-1} + W_{n-1} \cdot c_V(s_n) \) on lower interval boundary?
Effect on Binary Representation of Lower Interval Boundary

\[ W_{n-1} \cdot c(s_n) = 0.\overbrace{00000\cdots0}^{z_{n-1}+V \text{ bits}} \underbrace{xxxxxx\cdots x}_{z_{n-1}-U \text{ bits}} 000\cdots \]

\[ A_{n-1} \cdot c_V(s_n) \quad (U+V \text{ bits}) \]

What is the effect of an update \( L_n = L_{n-1} + W_{n-1} \cdot c_V(s_n) \) on lower interval boundary?

\[ L_{n-1} = 0.\overbrace{aaaaa\cdots a}^{z_{n-1}-U \text{ bits}} \overbrace{0111111\cdots1}^{z_{n-1}-c_{n-1}-U} \underbrace{xxxxx\cdots x}_{c_{n-1}} 00000\cdots \]

\[ U+V \]
Effect on Binary Representation of Lower Interval Boundary

\[ W_{n-1} \cdot c(s_n) = 0. \underbrace{00000 \cdots 0}_{z_{n-1} - U \text{ bits}} \underbrace{xxxxxxx \cdots x}_{A_{n-1} \cdot c_V(s_n)} 000 \cdots \]

What is the effect of an update \( L_n = L_{n-1} + W_{n-1} \cdot c_V(s_n) \) on lower interval boundary?

\[ L_{n-1} = 0. \underbrace{aaaaa \cdots a}_{z_{n-1} - c_{n-1} - U} \underbrace{011111 \cdots 1}_{c_{n-1}} \underbrace{xxxxx \cdots x}_{U + V} 00000 \cdots \]

\[ \rightarrow \text{Trailing bits: Equal to 0, but maybe changed later} \]
Effect on Binary Representation of Lower Interval Boundary

\[ W_{n-1} \cdot c(s_n) = 0. \underbrace{00000 \cdots 0}_{z_{n-1}-U \text{ bits}} \underbrace{xxxxxx \cdots x}_{A_{n-1} \cdot c_V(s_n)} 000 \cdots \]

What is the effect of an update \( L_n = L_{n-1} + W_{n-1} \cdot c_V(s_n) \) on lower interval boundary?

\[ L_{n-1} = 0. \underbrace{aaaaa \cdots a}_{z_{n-1}-U \text{ bits}} \underbrace{011111 \cdots 1}_{z_{n-1}-c_{n-1}-U \text{ bits}} \underbrace{xxxxx \cdots x}_{c_{n-1}} 00000 \cdots \]

- **Trailing bits:** Equal to 0, but maybe changed later
- **Active bits:** Directly modified by the update \( L_n = L_{n-1} + W_{n-1} \cdot c(s_n) \)
Effect on Binary Representation of Lower Interval Boundary

\[ W_{n-1} \cdot c(s_n) = 0. \underbrace{00000 \cdots 0}_{z_{n-1} - U \text{ bits}} \underbrace{xxxxxx \cdots x}_{A_{n-1} \cdot c_V(s_n)} 000 \cdots \]

What is the effect of an update \( L_n = L_{n-1} + W_{n-1} \cdot c_V(s_n) \) on lower interval boundary?

\[ L_{n-1} = 0. \underbrace{aaaaa \cdots a}_{z_{n-1} - c_{n-1} - U \text{ bits}} \underbrace{011111 \cdots 1}_{z_{n-1} - c_{n-1} - U \text{ bits}} \underbrace{xxxxx \cdots x}_{U + V \text{ bits}} 00000 \cdots \]

- **Trailing bits:** Equal to 0, but maybe changed later
- **Active bits:** Directly modified by the update \( L_n = L_{n-1} + W_{n-1} \cdot c(s_n) \)
- **Outstanding bits:** May be modified by a carry from the active bits
Effect on Binary Representation of Lower Interval Boundary

\[
W_{n-1} \cdot c(s_n) = 0.00000\cdots0 \overline{xxxxxx \cdots x} 000\cdots
\]

\[
z_{n-1} - U \text{ bits } \quad A_{n-1} \cdot c_V(s_n)
\]

\[
(U+V \text{ bits})
\]

What is the effect of an update \( L_n = L_{n-1} + W_{n-1} \cdot c_V(s_n) \) on lower interval boundary?

\[
L_{n-1} = 0.\overline{aaaaa\cdots a} 0111111\cdots1 \overline{xxxxx \cdots x} 00000\cdots
\]

\[
z_{n-1} - U \text{ bits }
\]

\[
z_{n-1} - c_{n-1} - U
\]

\[
c_{n-1}
\]

\[
U+V
\]

\[
\text{settled bits}
\]

\[
\text{outstanding bits}
\]

\[
\text{active bits}
\]

\[
\text{trailing bits}
\]

→ **Trailing bits:** Equal to 0, but maybe changed later

→ **Active bits:** Directly modified by the update \( L_n = L_{n-1} + W_{n-1} \cdot c(s_n) \)

→ **Outstanding bits:** May be modified by a carry from the active bits

→ **Settled bits:** Not modified in any following interval update
Representation of Lower Interval Boundary

\[ L_n = 0. \overbrace{aaaa \cdots a}^{z_n - U \text{ bits}} \overbrace{0111111 \cdots 1}^{z_n - c_n - U} \overbrace{xxxx \cdots x}^{c_n \text{ outstanding bits}} \overbrace{00000 \cdots}^{U + V \text{ active bits}} \]

- **settled bits**: \[ z_n - c_n - U \]
- **outstanding bits**: \( c_n \)
- **active bits**: \( U + V \)
- **trailing bits**: \( 00000 \cdots \)
Representation of Lower Interval Boundary

\[ L_n = 0.\overbrace{aaaaa\cdots a}^{z_n-U \text{ bits}} \overbrace{0111111\cdots 1}^{z_n-c_n-U \text{ settled bits}} \overbrace{xxxxx\cdots x}^{c_n \text{ outstanding bits}} \overbrace{00000\cdots}^{U+V \text{ active bits}} \]

- **Active bits:**
  - Represent as \((U+V)\)-bit integer \(B_n\)
  - Intermediate values \(B_{n-1} + A_{n-1} \cdot c_V(s_n)\) require \((U+V+1)\)-bit integer
Active bits:

- Represent as \((U + V)\)-bit integer \(B_n\)
- Intermediate values \(B_{n-1} + A_{n-1} \cdot c_V(s_n)\) require \((U + V + 1)\)-bit integer

Outstanding bits:

- Represent as integer counter \(c_n\) (trailing \(c_n - 1\) bits are equal to 1)
Representation of Lower Interval Boundary

\[ L_n = 0.\overbrace{aaaaa \cdots a}^{z_n-U \text{ bits}} \overbrace{0111111 \cdots 1}^{z_n-c_n-U \text{ settled bits}} \overbrace{xxxxx \cdots x}^{c_n \text{ outstanding bits}} \overbrace{00000 \cdots}^{U+V \text{ active bits}} \]

- **Active bits:**
  - Represent as \((U+V)\)-bit integer \(B_n\)
  - Intermediate values \(B_{n-1} + A_{n-1} \cdot c_V(s_n)\) require \((U+V+1)\)-bit integer

- **Outstanding bits:**
  - Represent as integer counter \(c_n\) (trailing \(c_n-1\) bits are equal to 1)

- **Settled bits:**
  - Output as soon as they become settled
Update of Probability Interval

\[
W_{n-1} = 0.00000000000000000\cdots0 \quad A_{n-1} (U)
\]

\[
L_{n-1} = 0.aaa\cdotsa01\cdots1 \quad 000\cdots0
\]

\[
W_n = 0.00000000000000000\cdots0 \quad 1xx\cdotsx 00000000\cdots0
\]

\[
L_n = 0.aaa\cdotsa xxx\cdotsxx \quad 00000000\cdots0
\]
Update of Probability Interval

\[
W_{n-1} = 0.0000000000000000000000000 \cdots \underbrace{0}_{A_{n-1}(U)}
\]
\[
L_{n-1} = 0.\underbrace{aaaaaaa \cdots a}_{z_{n-1} - c_{n-1} - U}011 \cdots 1 \underbrace{000000000}_{B_{n-1}(U + V)}
\]
\[
W_n = 0.0000000000000000000000000 \cdots \underbrace{0}_{A_n(U)}
\]
\[
L_n = 0.\underbrace{aaaaaaa \cdots a}_{z_{n-1} - c_{n-1} - U} \underbrace{xxxxxxxx \cdots xxx}_{c_{n-1} + \Delta z} \underbrace{000000000}_{B_n(U + V)}
\]

**Interval update**:

\[
A_n^* = A_{n-1} \cdot p_V(s_n)
\]
\[
B_n^* = B_{n-1} + A_{n-1} \cdot c_V(s_n)
\]
\[
\Delta z = \text{number of leading zeros in } (U+V)\text{-bit integer } A_n^*
\]
\[
A_n = (A_n^* \ll \Delta z) \gg V
\]
\[
B_n = (B_n^* \ll \Delta z) \& ((1 \ll (U + V)) - 1)
\]
Output of Settled Bits and Update of Outstanding Counter

Investigate intermediate \((U + V + 1)\)-bit integer \(B^*_n\) and outstanding counter \(c_{n-1}\)

\[
B^*_n : \\
\Delta z \text{ bits} \quad c \quad ZZ \cdots ZZ \quad U + V - \Delta z \text{ bits} \\
\text{(trailing} \ U + V - \Delta z \text{ bits are first bits of new} \ B_n) \\
c_{n-1} : (\text{settled bits}) \quad 0111 \cdots 1 \quad 0000000000 \cdots \\
\quad \underbrace{c_{n-1} \text{ bits}} \quad \text{(outstanding bits can be inverted by carry} \ c)
Output of Settled Bits and Update of Outstanding Counter

Investigate intermediate \((U + V + 1)\)-bit integer \(B^*_n\) and outstanding counter \(c_{n-1}\)

\[
B^*_n : \quad \begin{array}{c}
\Delta z \text{ bits} \\
c \\
U + V - \Delta z \text{ bits}
\end{array}
\]
\[
c_{n-1} : (\text{settled bits}) \underbrace{0111 \cdots 1}_{c_{n-1} \text{ bits}} 0000000000 \cdots
\]
\[(\text{trailing } U + V - \Delta z \text{ bits are first bits of new } B_n)\]

1. Check for carry
   - If \((c = 1)\), output one '1' and \((c_{n-1} - 2)\) '0's, remove carry (set \(c = 0\)), and set \(c_{n-1} = 1\)
   - From now on, \(B^*_n\) is considered a \((U + V)\)-bit integer
Output of Settled Bits and Update of Outstanding Counter

Investigate intermediate \((U + V + 1)\)-bit integer \(B_n^*\) and outstanding counter \(c_{n-1}\)

\[
B_n^* : \quad \overbrace{\Delta z \text{ bits}}^{c} \quad \overbrace{U + V - \Delta z \text{ bits}}^{\text{ZZ} \cdots \text{ZZ}} \quad \overbrace{\text{XXX} \cdots \text{XXX}}^{\text{(trailing } U + V - \Delta z \text{ bits are first bits of new } B_n)}
\]

\[
c_{n-1} : \text{(settled bits)} \quad \overbrace{0111 \cdots 1}^{c_{n-1} \text{ bits}} \quad 0000000000 \cdots \quad \text{(outstanding bits can be inverted by carry } c)\]

1. Check for carry
   - If \((c = 1)\), output one '1' and \((c_{n-1} - 2)\)'0's, remove carry (set \(c = 0\)), and set \(c_{n-1} = 1\)
   - From now on, \(B_n^*\) is considered a \((U + V)\)-bit integer

2. If \((\Delta z > 0)\), determine number \(n_1\) of trailing ones in \(\Delta z\) leading bits of \((U + V)\)-bit integer \(B_n^*\)
Output of Settled Bits and Update of Outstanding Counter

Investigate intermediate \((U + V + 1)\)-bit integer \(B_n^*\) and outstanding counter \(c_{n-1}\)

\[
B_n^* : \begin{array}{c}
\Delta z \text{ bits } \\
c \begin{array}{c}
\text{ZZ } \cdots \text{ZZ } \\
\text{XXX } \cdots \text{XXX }
\end{array}
\end{array} \quad \begin{array}{c}
U + V - \Delta z \text{ bits }
\end{array}
\]  

(trailing \(U + V - \Delta z\) bits are first bits of new \(B_n\))

\[c_{n-1} : (\text{settled bits}) \quad 0111 \cdots 1 \quad 0000000000 \cdots \quad (\text{outstanding bits can be inverted by carry } c)
\]

1. Check for carry
   
   - If \((c = 1)\), output one '1' and \((c_{n-1} - 2)\) '0's, remove carry (set \(c = 0\)), and set \(c_{n-1} = 1\)
   
   - From now on, \(B_n^*\) is considered a \((U + V)\)-bit integer

2. If \((\Delta z > 0)\), determine number \(n_1\) of trailing ones in \(\Delta z\) leading bits of \((U + V)\)-bit integer \(B_n^*\)
   
   a. If \((n_1 < \Delta z)\), output all \(c_{n-1}\) outstanding bits, output first \((\Delta z - n_1 - 1)\) bits of \(B_n^*\), set \(c_n = n_1 + 1\)
Output of Settled Bits and Update of Outstanding Counter

Investigate intermediate \((U + V + 1)\)-bit integer \(B_n^*\) and outstanding counter \(c_{n-1}\)

\[
B_n^* : \quad \begin{array}{c}
\text{\Delta z bits} \\
\text{ZZ \ldots ZZ} \\
\text{U+V-\Delta z bits} \\
\text{xxx \ldots xxx}
\end{array} \\ c_{n-1} : (\text{settled bits}) \quad 0111 \ldots 1 \\
\underbrace{0000000000 \ldots}_{c_{n-1} \text{ bits}} \\
(\text{trailing } U+V-\Delta z \text{ bits are first bits of new } B_n)
\]

(\text{outstanding bits can be inverted by carry } c)

1. Check for carry
   - If \((c = 1)\), output one '1' and \((c_{n-1} - 2)\) '0's, remove carry (set \(c = 0\)), and set \(c_{n-1} = 1\)
   - From now on, \(B_n^*\) is considered a \((U+V)\)-bit integer

2. If \((\Delta z > 0)\), determine number \(n_1\) of trailing ones in \(\Delta z\) leading bits of \((U+V)\)-bit integer \(B_n^*\)
   - a) If \((n_1 < \Delta z)\), output all \(c_{n-1}\) outstanding bits, output first \((\Delta z - n_1 - 1)\) bits of \(B_n^*\), set \(c_n = n_1 + 1\)
   - b) If \((n_1 = \Delta z \&\& c_{n-1} > 0)\), increase outstanding counter \(c_n = c_{n-1} + n_1\)
Output of Settled Bits and Update of Outstanding Counter

Investigate intermediate \((U + V + 1)\)-bit integer \(B_n^*\) and outstanding counter \(c_{n-1}\)

\[
B_n^* : \begin{array}{c}
\Delta z \text{ bits} \\
U + V - \Delta z \text{ bits}
\end{array} \begin{array}{c}
c \quad \text{ZZ} \cdots \text{ZZ} \\
\text{xxx} \cdots \text{xxx}
\end{array}
\]  
(trailing \(U + V - \Delta z\) bits are first bits of new \(B_n\))

\[
c_{n-1} : (\text{settled bits}) \begin{array}{c}
0111 \cdots 1
\end{array} \begin{array}{c}
c_{n-1} \text{ bits}
\end{array} \begin{array}{c}
\text{000000000} \cdots
\end{array}
\]
(outstanding bits can be inverted by carry \(c\))

1. Check for carry
   - If \((c = 1)\), output one '1' and \((c_{n-1} - 2)\) '0's, remove carry (set \(c = 0\)), and set \(c_{n-1} = 1\)
   - From now on, \(B_n^*\) is considered a \((U + V)\)-bit integer

2. If \((\Delta z > 0)\), determine number \(n_1\) of trailing ones in \(\Delta z\) leading bits of \((U + V)\)-bit integer \(B_n^*\)
   - If \((n_1 < \Delta z)\), output all \(c_{n-1}\) outstanding bits, output first \((\Delta z - n_1 - 1)\) bits of \(B_n^*\), set \(c_n = n_1 + 1\)
   - If \((n_1 = \Delta z \land c_{n-1} > 0)\), increase outstanding counter \(c_n = c_{n-1} + n_1\)
   - If \((n_1 = \Delta z \land c_{n-1} = 0)\), output first \(\Delta z\) bits of \(B_n^*\), set \(c_n = 0\) (rare case)
Termination of Arithmetic Codeword

**Total Number of Bits for Arithmetic Codeword** (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil$$
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \lceil a - \log_2 W_N \rceil = \lceil a - \log_2 (A_N \cdot 2^{-z_n}) \rceil$$
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_n}) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor$$
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword \((\text{with } a = 1 \text{ for prefix-free, and } a = 0 \text{ otherwise})\)

\[
K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_n}) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor = a + z_N - U + 1
\]
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_n}) \right\rceil = a + z_n - \left\lceil \log_2 A_N \right\rceil = a + z_N - U + 1$$

$\Rightarrow$ Note: The sum of settled and outstanding bits is $z_N - U$
Termination of Arithmetic Codeword

**Total Number of Bits for Arithmetic Codeword** (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_N}) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor = a + z_N - U + 1$$

- **Note:** The sum of settled and outstanding bits is $z_N - U$
- **Need to output all** $c_N$ **outstanding bits and first** $(1+a)$ **bits of** $B_N$
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_n}) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor = a + z_N - U + 1$$

- Note: The sum of settled and outstanding bits is $z_N - U$
- Need to output all $c_N$ outstanding bits and first $(1+a)$ bits of $B_N$

Codeword Termination

1. Rounding up lower interval boundary
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_n}) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor = a + z_N - U + 1$$

- Note: The sum of settled and outstanding bits is $z_N - U$
- Need to output all $c_N$ outstanding bits and first $(1+a)$ bits of $B_N$

Codeword Termination

1. Rounding up lower interval boundary
   - If any of the last $X = (U + V - a - 1)$ bits in $B_N$ is equal to 1, then
     - Set $B_N = B_N + (1 \ll X)$ (rounding up lower interval boundary to required precision)
     - If carry bit is set in $B_N$, handle carry as in normal interval update
Termination of Arithmetic Codeword

**Total Number of Bits for Arithmetic Codeword**  (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 \left( A_N \cdot 2^{-z_n} \right) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor = a + z_N - U + 1$$

- Note: The sum of settled and outstanding bits is $z_N - U$
- Need to output all $c_N$ outstanding bits and first $(1+a)$ bits of $B_N$

**Codeword Termination**

1. Rounding up lower interval boundary
   - If any of the last $X = (U + V - a - 1)$ bits in $B_N$ is equal to 1, then
     - Set $B_N = B_N + (1 \ll X)$  (rounding up lower interval boundary to required precision)
     - If carry bit is set in $B_N$, handle carry as in normal interval update

2. Output all outstanding bits (one '0' and $(c_N - 1)$ times '1')
Termination of Arithmetic Codeword

Total Number of Bits for Arithmetic Codeword (with $a = 1$ for prefix-free, and $a = 0$ otherwise)

$$K = \left\lceil a - \log_2 W_N \right\rceil = \left\lceil a - \log_2 (A_N \cdot 2^{-z_n}) \right\rceil = a + z_n - \left\lfloor \log_2 A_N \right\rfloor = a + z_N - U + 1$$

- Note: The sum of settled and outstanding bits is $z_N - U$
- Need to output all $c_N$ outstanding bits and first $(1+a)$ bits of $B_N$

Codeword Termination

1. Rounding up lower interval boundary
   - If any of the last $X = (U+V-a-1)$ bits in $B_N$ is equal to 1, then
     - Set $B_N = B_N + (1 \ll X)$ (rounding up lower interval boundary to required precision)
     - If carry bit is set in $B_N$, handle carry as in normal interval update

2. Output all outstanding bits (one '0' and $(c_N - 1)$ times '1')

3. Output $(a + 1)$ most significant bits of $B_N$
Summary: Arithmetic Encoding

1 Initialization: $A_0 = 2^U - 1$, $B_0 = 0$, $c_0 = 0$, mask = $(1 \ll (U+V)) - 1$

2 Iterative encoding (for $n = 1$ to $N$)
   a Calculate: $A_n^* = A_{n-1} \cdot p_V(s_n)$ \hspace{1cm} $(U + V \text{ bits})$
   $B_n^* = B_{n-1} + A_{n-1} \cdot c_V(s_n)$ \hspace{1cm} $(U + V + 1 \text{ bits})$
   b Determine number $\Delta z$ of leading zeros in $(U+V)$-bit integer $A_n^*$
   c Check for carry bit in $B_n^*$ (and update $c_{n-1}$ and settled bits accordingly)
   d Investigate $\Delta z$ leading bits in $(U+V)$ bits of $B_n^*$
      → Output new settled bits and update counter $c_n$ for new outstanding bits
   e Update: $A_n = (A_n^* \ll \Delta z) \gg V$
      $B_n = (B_n^* \ll \Delta z) \& \text{mask}$

3 Codeword Termination:
   → Round up $B_N$ (check for carry as in iterations)
   → Output $c_N$ outstanding bits
   → Output two most significant bits of $B_N$ (only 1 bit for non-prefix-free variant)
Arithmetic Encoding Example

Example: Preparation

- **Encoding example**
  - IID source with symbol alphabet \{A, N, B\}
  - Pmf is given by \{1/2, 1/3, 1/6\}
  - Consider arithmetic coding with \(V = 4\) and \(U = 4\)
  - Symbol sequence “BANANA”

- Preparation: Quantization of pmf (and cmf) with \(V = 4\) bits

<table>
<thead>
<tr>
<th></th>
<th>(p(a))</th>
<th>(p(a) \cdot 2^4)</th>
<th>(p_V(a))</th>
<th>(c_V(a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1/2</td>
<td>16/2 = 8.00</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>1/3</td>
<td>16/3 \approx 5.33</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>1/6</td>
<td>16/6 \approx 2.66</td>
<td>3</td>
<td>13</td>
</tr>
</tbody>
</table>

- Note: Quantized pmf \(p_V(a)\) fulfills the requirement \(\sum p_V(a) \leq 2^V\)
## Arithmetic Encoding Example (continued)

### Example: Step 1

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
<tbody>
<tr>
<td>initialization</td>
<td></td>
<td></td>
<td>$A_0 = 15 = '1111'$ (2^4 - 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_0 = 0$ (&quot;&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_0 = 0 = '0000 0000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;&quot;</td>
</tr>
<tr>
<td>&quot;B&quot;</td>
<td>3</td>
<td>13</td>
<td>$A_1^* = A_0 \cdot p_V = 15 \cdot 3 = 45 = '0010 1101'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_1^* = B_0 + A_0 \cdot c_V = 0 + 15 \cdot 13 = 195 = '0 1100 0011'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta z = 2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>output = &quot;11&quot; (cannot be outstanding bits)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_1 = 0$ (&quot;&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_1 = '1011' = 11$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_1 = '0000 1100' = 12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;11&quot;</td>
</tr>
</tbody>
</table>
### Arithmetic Encoding Example (continued)

#### Example: Step 2

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_1 = 11 = '1011'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_1 = 0$ ('')</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_1 = 12 = '0000 1100'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;11&quot;</td>
</tr>
<tr>
<td>&quot;A&quot;</td>
<td>8</td>
<td>0</td>
<td>$A_2^* = A_1 \cdot p_V = 11 \cdot 8 = 88 = '0101 1000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_2^* = B_1 + A_1 \cdot c_V = 12 + 11 \cdot 0 = 12 = '0 0000 1100'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta z = 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>output = &quot;&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_2 = 1$ ('0')</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_2 = '1011'$ = 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_2 = '0001 1000'$ = 24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;11&quot;</td>
</tr>
</tbody>
</table>
Arithmetic Encoding Example (continued)

Example: Step 3

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
<tbody>
<tr>
<td>after step 2</td>
<td></td>
<td></td>
<td>( A_2 = 11 = '1011' )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( c_2 = 1 ) ('0')</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( B_2 = 24 = '0001 1000' )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;11&quot;</td>
</tr>
<tr>
<td>“N”</td>
<td>5 8</td>
<td></td>
<td>( A^*_3 = A_2 \cdot p_V = 11 \cdot 5 = 55 = '0011 0111' )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( B^*_3 = B_2 + A_2 \cdot c_V = 24 + 11 \cdot 8 = 112 = '0 0111 0000' )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \Delta z = 2 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>output = “0” (old outstanding bit)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( c_3 = 2 ) ('01')</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( A_3 = '1101' = 13 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( B_3 = '1100 0000' = 192 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;110&quot;</td>
</tr>
</tbody>
</table>
### Example: Step 4

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
<tbody>
<tr>
<td>after step 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| “A” | 8 | 0 | $A_3 = 13 = '1101'$  
$c_3 = 2$  
($'01'$)  
$B_3 = 192 = '1100 0000'$  
bitstream = “110” |
| | | | $A^*_4 = A_3 \cdot p_V = 13 \cdot 8 = 104 = '0110 1000'$  
$B^*_4 = B_3 + A_3 \cdot c_V = 192 + 13 \cdot 0 = 192 = '0 1100 0000'$  
$\Delta z = 1$ |
| | | | output = “”  
$c_4 = 3$  
($'011'$)  
$A_4 = '1101' = 13$  
$B_4 = '1000 0000' = 128$  
bitstream = “110” |
### Arithmetic Encoding Example (continued)

**Example: Step 5**

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
</table>
| after step 4 | | | $A_4 = 13 = '1101'$  
| | | | $c_4 = 3$ ('011')  
| | | | $B_4 = 128 = '1000 0000'$  
| | | | bitstream = "110" |
| “N” | 5 8 | | $A^*_5 = A_4 \cdot p_V = 13 \cdot 5 = 65 = '0100 0001'$  
| | | | $B^*_5 = B_4 + A_4 \cdot c_V = 128 + 13 \cdot 8 = 232 = '0 1110 1000'$  
| | | | $\Delta z = 1$  
| | | output = “” |  
| | | | $c_5 = 4$ ('0111')  
| | | | $A_5 = '1000'$ = 8  
| | | | $B_5 = '1101 0000'$ = 208  
| | | | bitstream = "110" |
## Arithmetic Encoding Example (continued)

### Example: Step 6

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
<tbody>
<tr>
<td>after step 5</td>
<td></td>
<td></td>
<td>$A_5 = 8 = '1000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_5 = 4$ (&quot;0111&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_5 = 208 = '1101 0000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;110&quot;</td>
</tr>
<tr>
<td>&quot;A&quot;</td>
<td>8</td>
<td>0</td>
<td>$A_6^* = A_5 \cdot p_V = 8 \cdot 8 = 64 = '0100 0000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_6^* = B_5 + A_5 \cdot c_V = 208 + 8 \cdot 0 = 208 = '0110 1000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta z = 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>output = &quot;&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_6 = 5$ (&quot;01111&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_6 = '1000'$ = 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_6 = '1010 0000'$ = 160</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;110&quot;</td>
</tr>
</tbody>
</table>
## Example: Codeword Termination

<table>
<thead>
<tr>
<th>$s_n$</th>
<th>$p_V$</th>
<th>$c_V$</th>
<th>parameter updates &amp; output</th>
</tr>
</thead>
<tbody>
<tr>
<td>after step 6</td>
<td></td>
<td></td>
<td>$A_6 = 8 = '1000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_6 = 5$ (&quot;0111&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B_6 = 160 = '1010 0000'$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;110&quot;</td>
</tr>
<tr>
<td>final rounding</td>
<td></td>
<td></td>
<td>$B^* = &quot;1 0010 0000&quot;$ (rounding up $B_6$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;1101 000&quot; (c$_6$ – 1 inverted bits)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c = 1$ (&quot;0&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B = &quot;0010 0000&quot;$</td>
</tr>
<tr>
<td>termination</td>
<td></td>
<td></td>
<td>final bitstream = &quot;1101 0000 0&quot; (c + 1 bits added)</td>
</tr>
</tbody>
</table>

→ Bitstream $b = "1101 0000 0"$ (for sequence $s = "BANANA"$)

→ Same number of bits ($K = 9$) as for Shannon-Fano-Elias coding
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder \((A_{n-1} \mapsto A_n)\)
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder ($A_{n-1} \mapsto A_n$)
- Arithmetic codeword “$b_0b_1b_2\cdots$” represents binary fraction $v = (0.b_0b_1b_2\cdots)_b$
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder ($A_{n-1} \mapsto A_n$)
- Arithmetic codeword “$b_0 b_1 b_2 \cdots$” represents binary fraction $v = (0.b_0 b_1 b_2 \cdots)_b$
- Iterative decoding: Output symbol $s_n$ which fulfills inequality
  \[
  L_{n-1} + W_{n-1} \cdot c(s_n) \leq v < L_{n-1} + W_{n-1} \cdot (c(s_n) + p(s_n))
  \]
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder \( (A_{n-1} \mapsto A_n) \)
- Arithmetic codeword “\( b_0 b_1 b_2 \cdots \)” represents binary fraction \( v = (0.b_0 b_1 b_2 \cdots)_b \)
- Iterative decoding: Output symbol \( s_n \) which fulfills inequality

\[
L_{n-1} + W_{n-1} \cdot c(s_n) \leq v < L_{n-1} + W_{n-1} \cdot (c(s_n) + p(s_n))
\]

Observation:

- Lower interval boundary cannot be represented with reasonable precision
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder ($A_{n-1} \mapsto A_n$)
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\]

Observation:

- Lower interval boundary cannot be represented with reasonable precision
  ➤ Idea: Subtract $L_{n-1}$ from the inequality
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder \((A_{n-1} \mapsto A_n)\)
- Arithmetic codeword “\(b_0b_1b_2\cdots\)” represents binary fraction \(v = (0.b_0b_1b_2\cdots)_b\)
- Iterative decoding: Output symbol \(s_n\) which fulfills inequality
  \[
  L_{n-1} + W_{n-1} \cdot c(s_n) \leq v < L_{n-1} + W_{n-1} \cdot (c(s_n) + p(s_n))
  \]

Observation:

- Lower interval boundary cannot be represented with reasonable precision
  - Idea: Subtract \(L_{n-1}\) from the inequality
  - Symbol \(s_n\) is identified by
    \[
    W_{n-1} \cdot c(s_n) \leq (v - L_{n-1}) < W_{n-1} \cdot (c(s_n) + p(s_n))
    \]
Arithmetic Decoding

Identification of Intervals

- Important: Same rounding of interval width as in encoder ($A_{n-1} \mapsto A_n$)
- Arithmetic codeword “$b_0 b_1 b_2 \cdots$” represents binary fraction $v = (0.b_0 b_1 b_2 \cdots)_b$
- Iterative decoding: Output symbol $s_n$ which fulfills inequality

$$L_{n-1} + W_{n-1} \cdot c(s_n) \leq v < L_{n-1} + W_{n-1} \cdot (c(s_n) + p(s_n))$$

Observation:

- Lower interval boundary cannot be represented with reasonable precision
  
  ➔ Idea: Subtract $L_{n-1}$ from the inequality

  ➔ Symbol $s_n$ is identified by

  $$W_{n-1} \cdot c(s_n) \leq (v - L_{n-1}) < W_{n-1} \cdot (c(s_n) + p(s_n))$$

  ➔ The value $u_{n-1} = v - L_{n-1}$ used in comparisons can be stored with $(U + V)$ bits, but needs to be updated after a symbol $s_n$ is decoded
Binary Representation of Representative Value \( u_n = v - L_n \)

\[
W_{n-1} = 0. \underbrace{0000000000000\cdots0}_{z_{n-1} - U} \underbrace{1xx\cdots x}_{U} 0000000000000\cdots
\]
Binary Representation of Representative Value $u_n = v - L_n$

\[ W_{n-1} = 0.0000000000000\ldots U \]

\[ W_{n-1} \cdot (c(s_n) + p(s_n)) = 0.00000000000\ldots U + V \]

\[ W_{n-1} \cdot c(s_n) = 0.00000000000\ldots U + V \]
Binary Representation of Representative Value $u_n = v - L_n$

\[ W_{n-1} = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1} - U} \overbrace{1xx \cdots x}^{U} 0000000000000 \cdots \]

\[ W_{n-1} \cdot (c(s_n) + p(s_n)) = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1} - U} \overbrace{xxx \cdots xxxxx}^{U + V} 000000000 \cdots \]

\[ v - L_{n-1} = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1} - U} \overbrace{xxx \cdots xxxxx}^{U + V} xxxxxxxxxx \cdots \]

\[ W_{n-1} \cdot c(s_n) = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1} - U} \overbrace{xxx \cdots xxxxx}^{U + V} 000000000 \cdots \]
Binary Representation of Representative Value \( u_n = v - L_n \)

\[
W_{n-1} = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1}-U} \overbrace{1xx \cdots x}^{U} 00000000000000 \cdots
\]

\[
W_{n-1} \cdot (c(s_n) + p(s_n)) = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1}-U} \overbrace{xxx \cdots xxxxx}^{U+V} 0000000000000 \cdots
\]

\[
v - L_{n-1} = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1}-U} \overbrace{xxx \cdots xxxxx}^{U+V} xxxxxxxxx \cdots
\]

\[
W_{n-1} \cdot c(s_n) = 0. \overbrace{0000000000000 \cdots 0}^{z_{n-1}-U} \overbrace{xxx \cdots xxxxx}^{U+V} 0000000000000 \cdots
\]

Use \((U+V)\)-bit integer \( u_n \) in comparisons (down-rounded value of \( v - L_n \))
Binary Representation of Representative Value $u_n = v - L_n$

$$W_{n-1} = 0.\overbrace{0000000000000\ldots 0}^{z_{n-1}-U} \overbrace{1xx\ldots x}^{U} 0000000000000\ldots$$

$$W_{n-1} \cdot (c(s_n) + p(s_n)) = 0.\overbrace{0000000000000\ldots 0}^{z_{n-1}-U} \overbrace{xxx\ldots xxxxx}^{U+V} 00000000\ldots$$

$$\nu - L_{n-1} = 0.\overbrace{0000000000000\ldots 0}^{z_{n-1}-U} \overbrace{xxx\ldots xxxxx}^{U+V} xx\ldots xxx\ldots$$

$$W_{n-1} \cdot c(s_n) = 0.\overbrace{0000000000000\ldots 0}^{z_{n-1}-U} \overbrace{xxx\ldots xxxxx}^{U+V} 00000000\ldots$$

Use $(U+V)$-bit integer $u_n$ in comparisons (down-rounded value of $\nu - L_n$)

1. Initialization: $u_0 = (\text{first } U+V \text{ bits from bitstream})$
Binary Representation of Representative Value $u_n = v - L_n$

$$W_{n-1} = 0.\overbrace{0000000000000\cdots0}^{z_{n-1}-U} \underbrace{1xx\cdots x}_{U} 0000000000000\cdots$$

$$W_{n-1} \cdot (c(s_n) + p(s_n)) = 0.\overbrace{0000000000000\cdots0}^{z_{n-1}-U} \underbrace{xxx\cdotsxxxx}_{U+V} 00000000\cdots$$

$$v - L_{n-1} = 0.\overbrace{0000000000000\cdots0}^{z_{n-1}-U} \underbrace{xxx\cdotsxxxx}_{U+V} xxxxxxxxx \cdots$$

$$W_{n-1} \cdot c(s_n) = 0.\overbrace{0000000000000\cdots0}^{z_{n-1}-U} \underbrace{xxx\cdotsxxxx}_{U+V} 00000000\cdots$$

Use $(U+V)$-bit integer $u_n$ in comparisons (down-rounded value of $v - L_n$)

1. **Initialization:** $u_0 = (first \ U+V \ bits \ from \ bitstream)$

2. **Update** $u_{n-1} \mapsto u_n$
Binary Representation of Representative Value $u_n = v - L_n$

\[
W_{n-1} = \frac{z_{n-1}-U}{U} 0.000000000000\cdots 0 1xx\cdots x 0000000000000\cdots
\]

\[
W_{n-1} \cdot (c(s_n) + p(s_n)) = \frac{z_{n-1}-U}{U+V} 0.000000000000\cdots 0 xxx\cdots xxxxxxx 0000000000\cdots
\]

\[
v - L_{n-1} = \frac{z_{n-1}-U}{U+V} 0.000000000000\cdots 0 xxx\cdots xxxxxxx xxxxxxxxx \cdots
\]

\[
W_{n-1} \cdot c(s_n) = \frac{z_{n-1}-U}{U+V} 0.000000000000\cdots 0 xxx\cdots xxxxxxx 0000000000\cdots
\]

Use $(U+V)$-bit integer $u_n$ in comparisons (down-rounded value of $v - L_n$)

1. **Initialization:** $u_0 = \text{(first } U+V \text{ bits from bitstream)}$

2. **Update** $u_{n-1} \mapsto u_n$
   - Subtract lower boundary: $u_n^* = u_{n-1} - A_{n-1} \cdot c_V(s_n)$
Binary Representation of Representative Value $u_n = v - L_n$

$$W_{n-1} = 0. \underbrace{0000000000000 \cdots 0}_{z_{n-1} - U} \underbrace{1xx \cdots x}_{U} \underbrace{00000000000000 \cdots}_{0}$$

$$W_{n-1} \cdot (c(s_n) + p(s_n)) = 0. \underbrace{0000000000000 \cdots 0}_{z_{n-1} - U} \underbrace{xxxxx \cdots xxx}_{U + V} \underbrace{0000000000 \cdots}_{0}$$

$$\nu - L_{n-1} = 0. \underbrace{0000000000000 \cdots 0}_{z_{n-1} - U} \underbrace{xxx \cdots xxxxx}_{U + V} \underbrace{xxxxxx \cdots}_{0}$$

$$W_{n-1} \cdot c(s_n) = 0. \underbrace{0000000000000 \cdots 0}_{z_{n-1} - U} \underbrace{xxxxx \cdots xxx}_{U + V} \underbrace{000000000 \cdots}_{0}$$

Use $(U + V)$-bit integer $u_n$ in comparisons (down-rounded value of $\nu - L_n$)

1. Initialization: $u_0 = \text{(first } U + V \text{ bits from bitstream)}$

2. Update $u_{n-1} \mapsto u_n$
   - Subtract lower boundary: $u^*_n = u_{n-1} - A_{n-1} \cdot c_V(s_n)$
   - Align with interval width: $u^{**}_n = u^*_n \ll \Delta z$ $\quad (\Delta z = \text{leading zeros in } A_n \cdot p_V(s_n))$
Binary Representation of Representative Value $u_n = \nu - L_n$

$$W_{n-1} = \begin{cases} z_{n-1} - U & 0.0000000000000 \cdots 0 \\ U & 1xx \cdots x 0000000000000 \cdots \end{cases}$$

$$W_{n-1} \cdot (c(s_n) + p(s_n)) = \begin{cases} z_{n-1} - U & 0.0000000000000 \cdots 0 \\ U + V & xxx \cdots xxxxx 000000000 \cdots \end{cases}$$

$$\nu - L_{n-1} = 0.0000000000000 \cdots 0 \text{ xxx } \cdots \text{ xxxxx } xxxxxxxx \cdots$$

$$W_{n-1} \cdot c(s_n) = \begin{cases} z_{n-1} - U & 0.0000000000000 \cdots 0 \\ U + V & xxx \cdots xxxxx 000000000 \cdots \end{cases}$$

Use $(U + V)$-bit integer $u_n$ in comparisons (down-rounded value of $\nu - L_n$)

1. Initialization: $u_0 = \text{(first } U + V \text{ bits from bitstream)}$

2. Update $u_{n-1} \mapsto u_n$
   - Subtract lower boundary: $u_n^* = u_{n-1} - A_{n-1} \cdot c_V(s_n)$
   - Align with interval width: $u_n^{**} = u_n^* \ll \Delta z$  \hspace{1cm} ($\Delta z =$ leading zeros in $A_n \cdot p_V(s_n)$)
   - $u_n^{**} \mapsto u_n$: Fill least significant bits with next $\Delta z$ bits from bitstream
Summary: Arithmetic Decoding

1 Initialization: \( A_0 = 2^U - 1, \)
\( u_0 = \) (first \( U + V \) bits from bitstream)

2 Iterative decoding (for \( n = 1 \) to \( N \))

a Identify next symbol: For \( k = 0, 1, 2, \cdots \) (loop over sorted symbol alphabet)
   - Calculate upper boundary \( U(a_k) = A_{n-1} \cdot (c_V(a_k) + p_V(a_k)) \)
   - If \( (u_{n-1} < U(a_k)) \), then
     - Output next symbol \( s_n = a_k \)
     - break loop over \( k \)

b Update parameters:
   - Calculate intermediate value: \( A^*_n = A_{n-1} \cdot p_V(s_n) \)
   - Determine number \( \Delta z \) of leading zeros in \((U + V)\)-bit integer \( A^*_n \)
     - \( A_n = (A^*_n \ll \Delta z) \gg V \)
     - \( u_n = ((u_{n-1} - A_{n-1} \cdot c_V(s_n)) \ll \Delta z) + (\) next \( \Delta z \) bits from bitstream)
Arithmetic Decoding Example

Decode Bitstream obtained in Encoding Example

- **Decoding example** (see encoding example)
  - IID source with symbol alphabet \{A, N, B\}
  - Pmf is given by \{1/2, 1/3, 1/6\}
  - Arithmetic coding with \(V = 4\) and \(U = 4\)

- Quantized pmf (and cmf) with \(V = 4\) bits

<table>
<thead>
<tr>
<th>(a)</th>
<th>(p(a))</th>
<th>(p(a) \cdot 2^4)</th>
<th>(pV(a))</th>
<th>(cV(a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1/2</td>
<td>16/2 = 8.00</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>1/3</td>
<td>16/3 \approx 5.33</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>1/6</td>
<td>16/6 \approx 2.66</td>
<td>3</td>
<td>13</td>
</tr>
</tbody>
</table>

- Bitstream \(b = "1101 0000 0"\)
### Example: Step 1

<table>
<thead>
<tr>
<th>$a$</th>
<th>$c_V$</th>
<th>$p_V$</th>
<th>decoding &amp; update</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;1101 0000 0(000 0000 0 · · ·)&quot;</td>
<td></td>
</tr>
<tr>
<td>initialization</td>
<td></td>
<td></td>
<td>$A_0 = 15 = '1111'$; $u_0 = 208 = '1101 0000'$</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>8</td>
<td>$U(A) = A_0 \cdot (c_V + p_V) = 15 \cdot (0 + 8) = 120$</td>
<td>$U(A) \leq u_0$</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>5</td>
<td>$U(N) = A_0 \cdot (c_V + p_V) = 15 \cdot (8 + 5) = 195$</td>
<td>$U(N) \leq u_0$</td>
</tr>
<tr>
<td>B</td>
<td>13</td>
<td>3</td>
<td>$U(B) = A_0 \cdot (c_V + p_V) = 15 \cdot (13 + 3) = 240$</td>
<td>$U(B) &gt; u_0$</td>
</tr>
</tbody>
</table>

$A_1^* = A_0 \cdot p_V(s_n) = 15 \cdot 3 = 45 = '0010 1101'$

$u_1^* = u_0 - A_0 \cdot c_V(s_n) = 208 - 15 \cdot 13 = 13 = '0000 1101'$

$\Delta z = 2$

$A_1 = '1011' = 11$

$u_1 = '0011 0100' = 52$

bitstream = "1101 0000 0(000 0000 0 · · ·)"
## Arithmetic Decoding Example (continued)

### Example: Step 2

<table>
<thead>
<tr>
<th>$a$</th>
<th>$c_V$</th>
<th>$p_V$</th>
<th>decoding &amp; update</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>after step 1</td>
<td></td>
<td></td>
<td>bitstream = “1101 0000 0(000 0000 0 · · ·)”</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>8</td>
<td>$U(A) = A_1 \cdot (c_V + p_V) = 11 \cdot (0 + 8) = 88$</td>
<td>$\rightarrow U(A) &gt; u_1$</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>5</td>
<td>$U(N) = A_1 \cdot (c_V + p_V) = 11 \cdot (8 + 5) = 143$</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>13</td>
<td>3</td>
<td>$U(B) = A_1 \cdot (c_V + p_V) = 11 \cdot (13 + 3) = 176$</td>
<td></td>
</tr>
<tr>
<td>$A_2^* = A_1 \cdot p_V(s_n) = 11 \cdot 8 = 88 = '0101 1000'$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$u_2^* = u_1 - A_1 \cdot c_V(s_n) = 52 - 11 \cdot 0 = 52 = '0011 0100'$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta z = 1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_2 = '1011'$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$u_2 = '0110 1000'$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bitstream = “1101 0000 0(000 0000 0 · · ·)”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Example: Step 3

| a | c
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>13</td>
</tr>
</tbody>
</table>

Decoding & update:

- **After step 2**
  - $A_2 = 11 = '1011'$
  - $u_2 = 104 = '0110 1000'$
  - Bitstream = "1101 0000 0(000 0000 0 \cdots)"

<table>
<thead>
<tr>
<th></th>
<th>$u(A)$</th>
<th>$u(N)$</th>
<th>$u(B)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$A_2 \cdot (c + p) = 11 \cdot (0 + 8) = 88$</td>
<td>$A_2 \cdot (c + p) = 11 \cdot (8 + 5) = 143$</td>
<td>$A_2 \cdot (c + p) = 11 \cdot (13 + 3) = 176$</td>
</tr>
</tbody>
</table>

- $U(A) = 11 \cdot (0 + 8) = 88 \rightarrow U(A) \leq u_2$
- $U(N) = 11 \cdot (8 + 5) = 143 \rightarrow U(N) > u_2$

- $U(B) = 11 \cdot (13 + 3) = 176$

| $A^*_3 = A_2 \cdot p(s_n) = 11 \cdot 5 = 55 = '0011 0111'$ | $u^*_3 = u_2 - A_2 \cdot c(s_n) = 104 - 11 \cdot 8 = 16 = '0001 0000'$ |

- $\Delta z = 2$
- $A_3 = '1101' = 13$
- $u_3 = '0100 0000' = 64$

- Bitstream = "1101 0000 0(000 0000 0 \cdots)"
### Example: Step 4

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>decoding &amp; update</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$c_V$</td>
<td>$p_V$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>after step 3</td>
<td></td>
<td></td>
<td>bitstream = “1101 0000 0(000 0000 0 · · ·)”</td>
<td></td>
</tr>
<tr>
<td>$A_3$</td>
<td>13 = ’$1101$’</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$u_3$</td>
<td>64 = ’0100 0000’</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>0</td>
<td>8</td>
<td>$U(A) = A_3 \cdot (c_V + p_V) = 13 \cdot (0 + 8) = 104 \rightarrow U(A) &gt; u_3$</td>
<td>$A$</td>
</tr>
<tr>
<td>$N$</td>
<td>8</td>
<td>5</td>
<td>$U(N) = A_3 \cdot (c_V + p_V) = 13 \cdot (8 + 5) = 169$</td>
<td></td>
</tr>
<tr>
<td>$B$</td>
<td>13</td>
<td>3</td>
<td>$U(B) = A_3 \cdot (c_V + p_V) = 13 \cdot (13 + 3) = 208$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_4^* = A_3 \cdot p_V(s_n) = 13 \cdot 8 = 104 = ’0110 1000’$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$u_4^* = u_3 - A_3 \cdot c_V(s_n) = 64 - 13 \cdot 0 = 64 = ’0100 0000’$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta z = 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_4 = ’1101’ = 13$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$u_4 = ’1000 0000’ = 128$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = “1101 0000 0(000 0000 0 · · ·)”</td>
<td></td>
</tr>
</tbody>
</table>

Heiko Schwarz (Freie Universität Berlin) — Data Compression: Arithmetic Coding
### Example: Step 5

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>decoding &amp; update</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>after step 4</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>c_V</td>
<td>p_V</td>
<td>bitstream = &quot;1101 0000 0(000 0000 0 · · ·)&quot;</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>8</td>
<td>( A_4 = 13 = '1101' )</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>5</td>
<td>( u_4 = 128 = '1000 0000' )</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>13</td>
<td>3</td>
<td>( U(A) = A_4 \cdot (c_V + p_V) = 13 \cdot (0 + 8) = 104 \rightarrow U(A) \leq u_4 )</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( U(N) = A_4 \cdot (c_V + p_V) = 13 \cdot (8 + 5) = 169 \rightarrow U(N) &gt; u_4 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( U(B) = A_4 \cdot (c_V + p_V) = 13 \cdot (13 + 3) = 208 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( A_5^* = A_4 \cdot p_V(s_n) = 13 \cdot 5 = 65 = '0100 0001' )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( u_5^* = u_4 - A_4 \cdot c_V(s_n) = 128 - 13 \cdot 8 = 24 = '0001 1000' )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \Delta z = 1 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( A_5 = '1000' = 8 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( u_5 = '0011 0000' = 48 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bitstream = &quot;1101 0000 0(000 0000 0 · · ·)&quot;</td>
<td></td>
</tr>
</tbody>
</table>
Example: Step 6 (last symbol)

<table>
<thead>
<tr>
<th>a</th>
<th>cv</th>
<th>pv</th>
<th>decoding &amp; update</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>after step 5</td>
<td>bitstream = “1101 0000 0(000 0000 0 · · ·)”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( A_5 = 8 = '1000' )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( u_5 = 48 = '0011 0000' )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>8</td>
<td>( U(A) = A_5 \cdot (c_v + p_v) = 8 \cdot (0 + 8) = 64 )</td>
<td>( \rightarrow U(A) &gt; u_4 ) ( A )</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>5</td>
<td>( U(N) = A_5 \cdot (c_v + p_v) = 8 \cdot (8 + 5) = 104 )</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>13</td>
<td>3</td>
<td>( U(B) = A_5 \cdot (c_v + p_v) = 8 \cdot (13 + 3) = 128 )</td>
<td></td>
</tr>
</tbody>
</table>

Note: Required some bits after end of the bitstream

- For non-prefix variant: Use bits equal to 0
- For prefix-free variant: Any bit values (0 or 1) can be used

bitstream “1101 0000 0” ⇔ symbol sequence “BANANA”
Coding Efficiency of Arithmetic Coding

Increase in Average Codeword Length relative to Shannon-Fano-Elias Coding

- Increase due to rounding of interval width

\[ \Delta \ell = \left\lceil - \log_2 W_N \right\rceil - \left\lceil - \log_2 p(s) \right\rceil < 1 + \log_2 \frac{p(s)}{W_N} \]

- Upper bound for increase in codeword length per symbol relative to infinite-precision Shannon-Fano-Elias coding

\[ \Delta \bar{\ell} < \frac{1}{N} + \log_2 (1 + 2^{1-U}) - \log_2 \left( 1 - \frac{2^{-V}}{p_{\text{min}}} \right) \]

(for a derivation see [Wiegand, Schwarz, “Source Coding”, page 51-52])

Example:

- Number of coded symbols \( N = 1000 \),
- Arithmetic precision: \( V = 16 \) and \( U = 12 \),
- Minimum probablity mass \( p_{\text{min}} = 0.02 \)

\( \Rightarrow \) Increase in codeword length is less than 0.003 bit per symbol
Binary Arithmetic Coding

- Binarization of $S \in \{a_1, a_2, \ldots, a_M\}$ produces $C \in \{0, 1\}$
  - Any prefix code can be used for binarization
  - Example: Truncated unary binarization

<table>
<thead>
<tr>
<th>$a_k$</th>
<th>number of bins $B$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$\cdots$</th>
<th>$C_{M-1}C_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2$</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_{M-2}$</td>
<td>$M-2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>1</td>
</tr>
<tr>
<td>$a_{M-1}$</td>
<td>$M-1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>0 1</td>
</tr>
<tr>
<td>$a_M$</td>
<td>$M-1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>0 0</td>
</tr>
</tbody>
</table>

Entropy unchanged due to binarization

Most popular form of arithmetic coding in practice
- Reduced complexity, better adaptation capabilities
- Used in JPEG-2000, H.264/AVC, H.265/HEVC, VVC
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<th>$a_k$</th>
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<th>$C_3$</th>
<th>$\cdots$</th>
<th>$C_{M-1}C_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2$</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$a_{M-2}$</td>
<td>$M-2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>1</td>
</tr>
<tr>
<td>$a_{M-1}$</td>
<td>$M-1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>0 1</td>
</tr>
<tr>
<td>$a_M$</td>
<td>$M-1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>0 0</td>
</tr>
</tbody>
</table>

- Entropy unchanged due to binarization $S \mapsto C$
Binary Arithmetic Coding

- Binarization of $S \in \{a_1, a_2, \ldots, a_M\}$ produces $C \in \{0, 1\}$

  ➔ Any prefix code can be used for binarization
  ➔ Example: Truncated unary binarization

<table>
<thead>
<tr>
<th>$a_k$</th>
<th>number of bins $B$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$\cdots$</th>
<th>$C_{M-1}C_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2$</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$a_{M-2}$</td>
<td>$M-2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>1</td>
</tr>
<tr>
<td>$a_{M-1}$</td>
<td>$M-1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>0 1</td>
</tr>
<tr>
<td>$a_M$</td>
<td>$M-1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\cdots$</td>
<td>0 0</td>
</tr>
</tbody>
</table>

  ➔ Entropy unchanged due to binarization $S \leftrightarrow C$

  ➔ Most popular form of arithmetic coding in practice

  ➔ Reduced complexity, better adaptation capabilities
  ➔ Used in JPEG-2000, H.264/AVC, H.265/HEVC, VVC
Arithmetic Coding in Practice

Complexity Reduction (example: CABAC in AVC and HEVC)

- Binary arithmetic coding
- Multiplication-free implementations
- Bypass mode: Low-complexity coding of bins with $p = 0.5$
Arithmetic Coding in Practice

Complexity Reduction  (example: CABAC in AVC and HEVC)
- Binary arithmetic coding
- Multiplication-free implementations
- Bypass mode: Low-complexity coding of bins with \( p = 0.5 \)

Practical Design Aspects

1. Context selection
   - Use reasonable context variables \( X = f(S_{n-1}, S_{n-2}, \ldots) \) for switching probability tables \( p(a | X) \)
   - Use context switching only when useful (certain bins)
Arithmetic Coding in Practice

Complexity Reduction (example: CABAC in AVC and HEVC)

- Binary arithmetic coding
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Practical Design Aspects

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   - Use reasonable context variables $X = f(S_{n-1}, S_{n-2}, \ldots)$ for switching probability tables $p(a | X)$
   - Use context switching only when useful (certain bins)

2. Estimate probabilities during coding
   - Choose appropriate “window sizes” for estimation
Arithmetic Coding in Practice

**Complexity Reduction** (example: CABAC in AVC and HEVC)
- Binary arithmetic coding
- Multiplication-free implementations
- Bypass mode: Low-complexity coding of bins with $p = 0.5$

**Practical Design Aspects**

1. **Context selection**
   - Use reasonable context variables $X = f(S_{n-1}, S_{n-2}, \cdots)$ for switching probability tables $p(a | X)$
   - Use context switching only when useful (certain bins)

2. **Estimate probabilities during coding**
   - Choose appropriate “window sizes” for estimation

3. **Suitably combine context selection and probability estimation**
Example: Stationary Markov Source

| a  | \( p(a|a_0) \) | \( p(a|a_1) \) | \( p(a|a_2) \) |
|----|----------------|----------------|----------------|
| \( a_0 \) | 0.90           | 0.15           | 0.05           |
| \( a_1 \) | 0.05           | 0.80           | 0.05           |
| \( a_2 \) | 0.05           | 0.05           | 0.60           |

\[ H(S) = 1.2575 \]
\[ \bar{H}(S) = 0.7331 \]

**Bounds for lossless coding**
- Entropy rate \( \bar{H}(S) \) for coding of infinitely many symbols
- Instantaneous entropy rate \( \bar{H}_{\text{inst}}(S, L) \) for coding \( L \) symbols

\[
\bar{H}_{\text{inst}}(S, L) = \frac{1}{L} H(S_0, S_1, \cdots, S_{L-1})
\]

**Coding experiment**
- Coding of 1 000 000 realizations of example stationary Markov source
- Calculate average codeword length for sequences of 1 to 1000 symbols
Comparison of Lossless Coding Techniques

Experimental Results for Stationary Markov Source

- Scalar Huffman code (3 codewords)
- Conditional Huffman code (3×3 codewords)
- Huffman code for fixed-length vectors (5 symbols, 243 codewords)
- Huffman code for variable-length vectors (17 codewords)
- Arithmetic coding (16 bits of precision for interval sizes and probabilities)

![Graph showing comparison of codeword lengths and entropy rates for different coding techniques.](image-url)
Summary of Lecture: Arithmetic Coding

Arithmetic Coding
- Suboptimal block code (finite precision realization of Shannon-Fano-Elias coding)
- No codeword table required
- Iterative construction of codeword
- Very close to entropy bound for $N \gg 1$
- Well suited for exploiting statistical dependencies
- Well suited for adapting probabilities during coding

Arithmetic Coding in Practice
- Typically only binary arithmetic coding (using simple structured codes for binarization)
- Low-complexity variants (multiplication-free, extra low-complex bypass mode)
- Adaptive probability models (updated after encoding/decoding each symbol)
- Often context-based selection of probability models
Exercise 1: Study Arithmetic Codec

On the course web-site, you find an implementation of an arithmetic encoder and decoder in C++:

- bitstream.h: classes for input and output bitstreams (header only)
- arithCoding.h: header for arithmetic encoder and decoder classes
- arithCoding.cpp: implementation of arithmetic encoder and decoder classes
- main.cpp: toy example for usage of arithmetic encoder and decoder

1. Study the arithmetic encoder and decoder in detail (compare it with the lecture slides)
2. Play around with the implementation, try different value for $U$. Try other example messages, pmfs (including values of $V$), and alphabets.
3. If you don’t want to use C++ for the following exercises, rewrite the implementation using a programming language of your choice

Note: We don’t need to modify the bitstream classes and the actual implementation of the arithmetic codec in the following exercises. We only need to modify the Pmf class (in main.cpp) and the usage of the arithmetic codec.
**Exercise 2: Arithmetic Coding of 8-bit Audio Data**

In the following we want to efficiently code the 8-bit audio file “audioData.raw” from the course web site.

1. Write a first encoder and decoder that use a fixed pmf. The encoder should do the following:
   - Count the number of samples (bytes) in the input file and write it as 32-bit integer at the beginning of the bitstream (use function OBitstream::addFixed(.)).
   - Estimate the marginal pmf, quantize it to $V$-bits of precision (choose suitable $V$, check validity).
   - Write all 256 probability masses $p_V(x)$ to the bitstream (each using $V$-bits).
   - Encode all samples of the input file using arithmetic coding with the estimated pmf.

2. Think about how you can estimate the pmf during encoding and decoding.
   Implement a pmf class that estimates the pmf during encoding and decoding (there is already a pure virtual function IPmf::update(.) in the interface class IPmf).
   In principle, you have to count symbols during encoding and decoding.

3. Once you have a working adaptive pmf, try to improve the codec by using conditional coding. That means, use 256 different adaptive pmfs in your encoder and decoder. The pmf for a current sample has to be selected based on the value of the previous sample.