How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

- Choose path with maximum bottleneck capacity.
- Choose path with sufficiently large bottleneck capacity.
- Choose the shortest augmenting path.
Capacity Scaling

Intuition:
- Choosing a path with the highest bottleneck increases the flow as much as possible in a single step.
- Don’t worry about finding the exact bottleneck.
- Maintain scaling parameter $\Delta$.
- $G_f(\Delta)$ is a sub-graph of the residual graph $G_f$ that contains only edges with capacity at least $\Delta$. 

![Diagram](image)
Algorithm 2 $\text{maxflow}(G, s, t, c)$

1: $\text{foreach } e \in E \text{ do } f_e \leftarrow 0$;
2: $\Delta \leftarrow 2^{\lceil \log_2 C \rceil}$
3: while $\Delta \geq 1$ do
4: $G_f(\Delta) \leftarrow \Delta$-residual graph
5: while there is augmenting path $P$ in $G_f(\Delta)$ do
6: $f \leftarrow \text{augment}(f, c, P)$
7: $\text{update}(G_f(\Delta))$
8: $\Delta \leftarrow \Delta/2$
9: return $f$
Capacity Scaling

Assumption:
All capacities are integers between 1 and $C$.

Invariant:
All flows and capacities are/remain integral throughout the algorithm.

Correctness:
The algorithm computes a maxflow:
- because of integrality we have $G_f(1) = G_f$
- therefore after the last phase there are no augmenting paths anymore
- this means we have a maximum flow.
Capacity Scaling

Lemma 1
There are \( \lceil \log C \rceil + 1 \) iterations over \( \Delta \).

Proof: obvious.

Lemma 2
Let \( f \) be the flow at the end of a \( \Delta \)-phase. Then the maximum flow is smaller than \( \text{val}(f) + m\Delta \).

Proof: less obvious, but simple:

- There must exist an \( s-t \) cut in \( G_f(\Delta) \) of zero capacity.
- In \( G_f \) this cut can have capacity at most \( m\Delta \).
- This gives me an upper bound on the flow that I can still add.
Lemma 3
There are at most $2m$ augmentations per scaling-phase.

Proof:
- Let $f$ be the flow at the end of the previous phase.
- $\text{val}(f^*) \leq \text{val}(f) + 2m\Delta$
- Each augmentation increases flow by $\Delta$.

Theorem 4
We need $\mathcal{O}(m \log C)$ augmentations. The algorithm can be implemented in time $\mathcal{O}(m^2 \log C)$. 