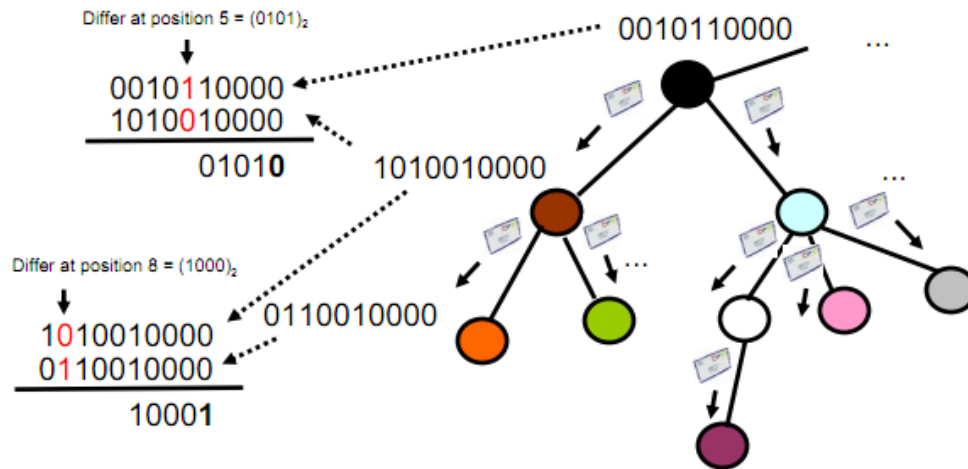


Distributed Computing over
Communication Networks:

Locality Lower Bounds

Vertex Coloring: Results so far?

E.g., on **trees** in **$\log^*(n)$ time**, down to **6 colors**...



Round 1

Is this optimal??

Idea:

root should have **label 0** (fixed)

in each step: send ID to c_v to all children;

receive c_p from parent and interpret as little-endian bit string: $c_p = c(k) \dots c(0)$

let i be smallest index where c_v and c_p differ

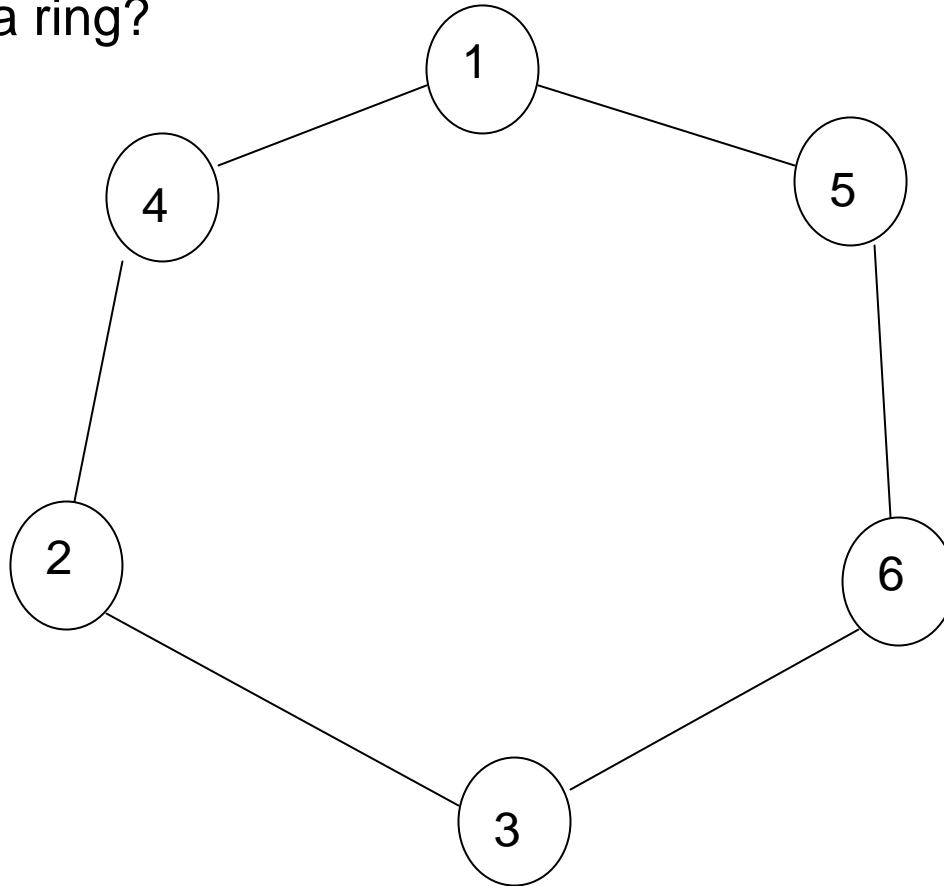
set new $c_v = i$ (as bit string) $\parallel c_v(i)$

until $c_v \in \{0, 1, 2, \dots, 5\}$ (at most 6 colors)

... and then **shift-down**: down to **3 colors** (same complexity).

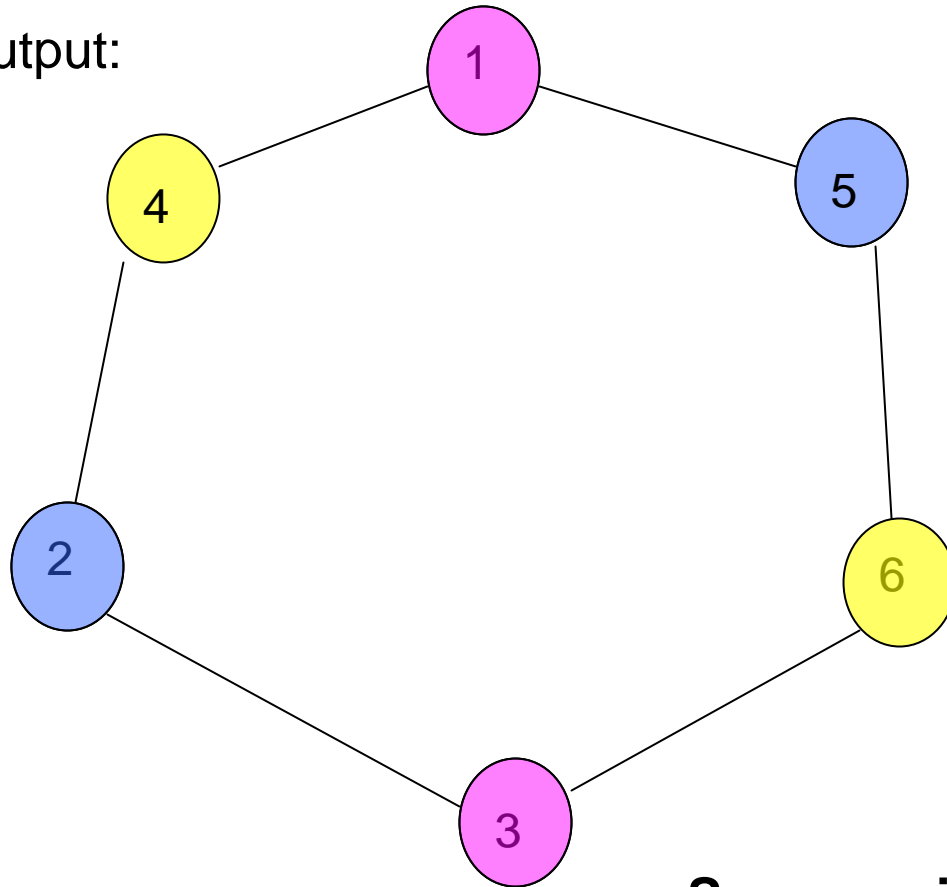
From trees to rings...

How to color a ring?



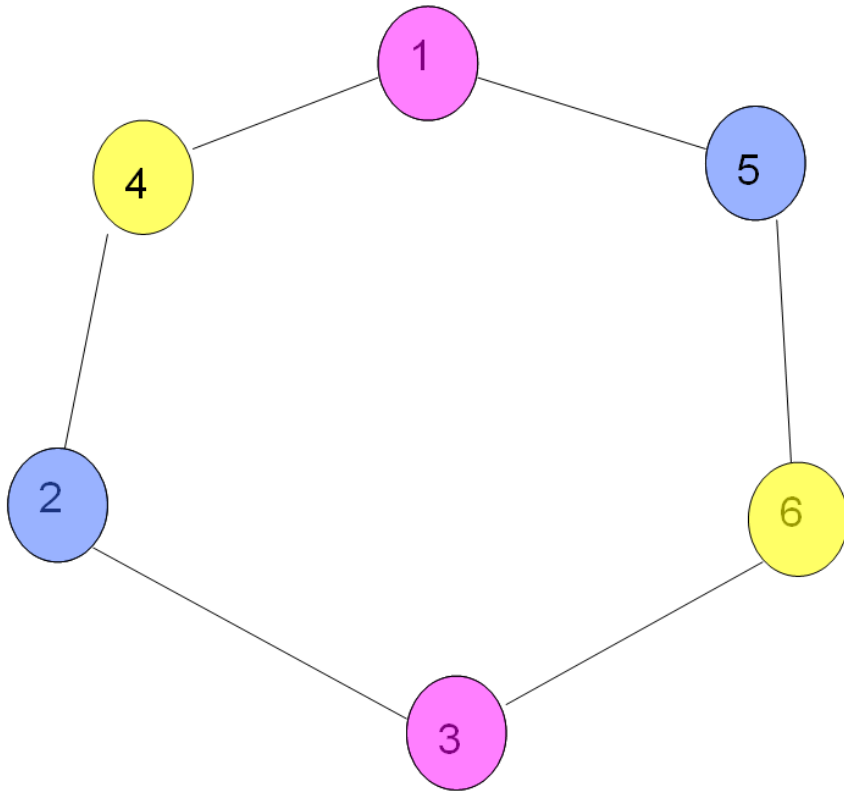
Ring Coloring

Possible output:



**See exercise session:
Algo for trees can be adapted!
So $\log^*(n)$ time...!**

Lower Bounds: First Thoughts and Outlook



Assume unique node IDs:

Lower bound for # colors **without communication?**

n

Lower bound for # colors with **one communication round?**

$\log n$

Lower bound for # colors with **two communication rounds?**

$\log \log n$

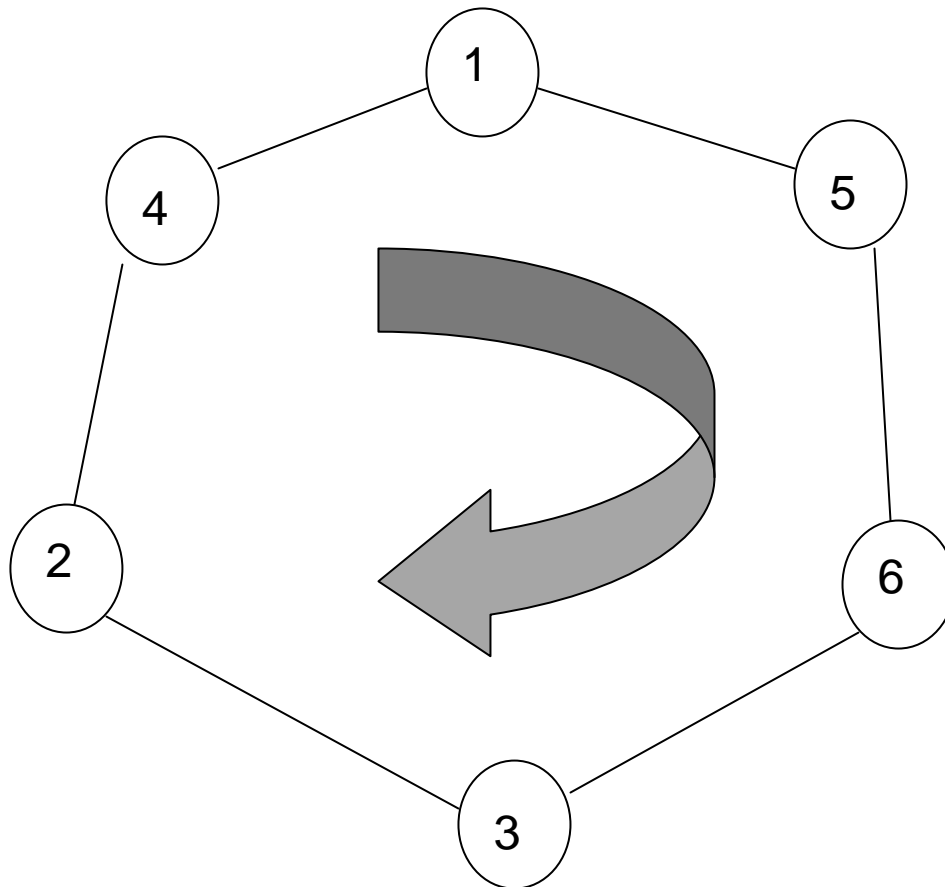
Lower bound for # colors with **$\log^* n$ communication rounds?**

$O(1)$

Lower Bounds: For simple ring, not tree....

3-color a ring: $\log^*(n)$ time is optimal!

How to prove?



Class of algos?

Need assumptions!

1. synchronous, **directed ring** (communication in both directions and nodes can differentiate between clockwise and counter-clockwise)
2. **IDs** from $1\dots n$ (not in order, otherwise trivial!)
3. **unbounded** message size

The **stronger assumptions** for which the lower bound is still high the better for us!

Remember „local algorithm“

is **symmetric**: each node executes the **same code**! We will see: can differentiate only in terms of neighborhoods...

Canonical Form of Distributed Algorithm?

What can a distributed algorithm do or learn in r rounds?

1. Initially, all nodes only know their own ID
2. As information needs at least r rounds to travel r hops, a node can only **learn about r -hop neighborhood!**

Note that any local r -round algorithm can be brought into **canonical form!**

Canonical Form

1. First, in r rounds: send **initial state** to nodes at distance r
2. Then: compute output based on **complete information** about r -hop neighborhood

In other words: we can **emulate any local algorithm** by making all communication first and then do all local computations! Why?

Example „leader election“:

Whether nodes only forward highest ID so far or whether all information is collected first and later selected does not make a difference!

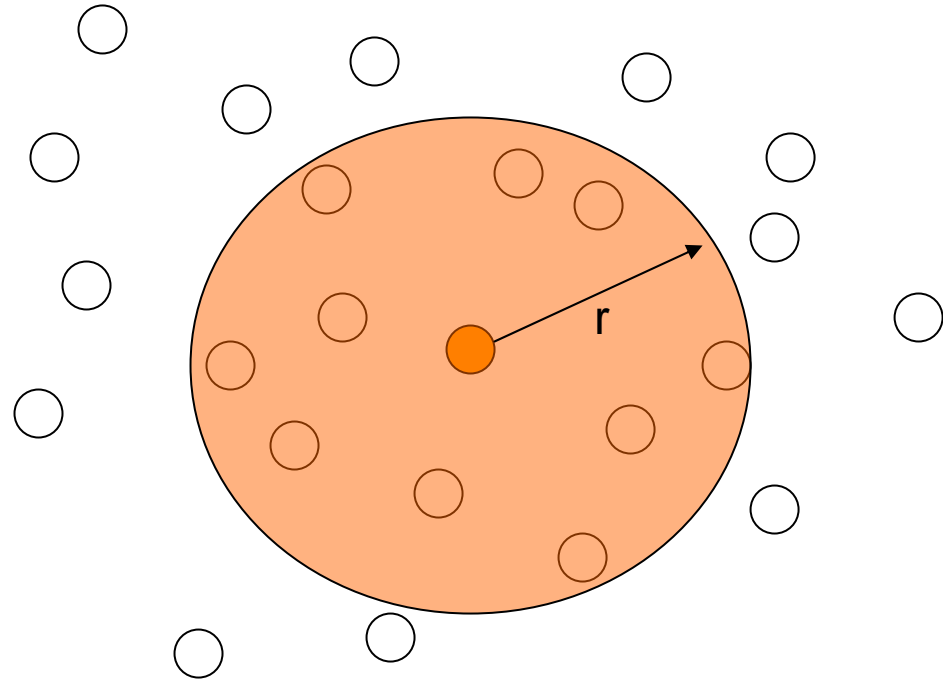
No Deterministic Local Algorithms Can Do More...

We can do all communication first and then do all local computations!

How to prove this?

Let **A** be any r -round algorithm. We can show that the canonical form algorithm **C** can compute all possible **messages that A may send as well**.

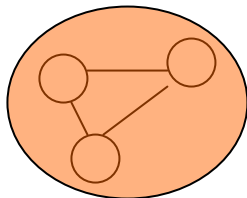
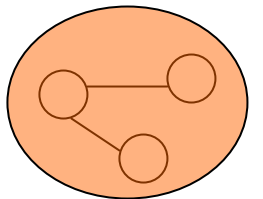
By **induction** over distance of nodes...:
if we can compute messages of first i rounds in $(r-i+1)$ -neighborhood, we have all information to compute first $(i+1)$ round messages in $(r-i)$ -neighborhood. See „Skript“. 😊



Takeaway

A local coloring algorithm can be seen as a function which takes neighborhoods and outputs colors.

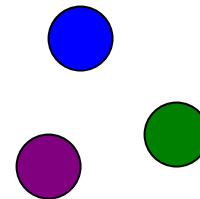
Set of neighborhoods



Local coloring algo



Vertex coloring



Local Views

This motivates the following definition:

r-Hop View

We call the collection of the initial states of all nodes in the r -neighborhood of a node v the „ r -hop view of v “.

Due to our canonical form lemma, this means that:

Deterministic r-Round Algo

A deterministic r -round algorithm A is a function that maps every possible r -hop view to the set of possible outputs.

Implication for nodes with same view?

Must produce **same output**, in any algorithm!

Roadmap

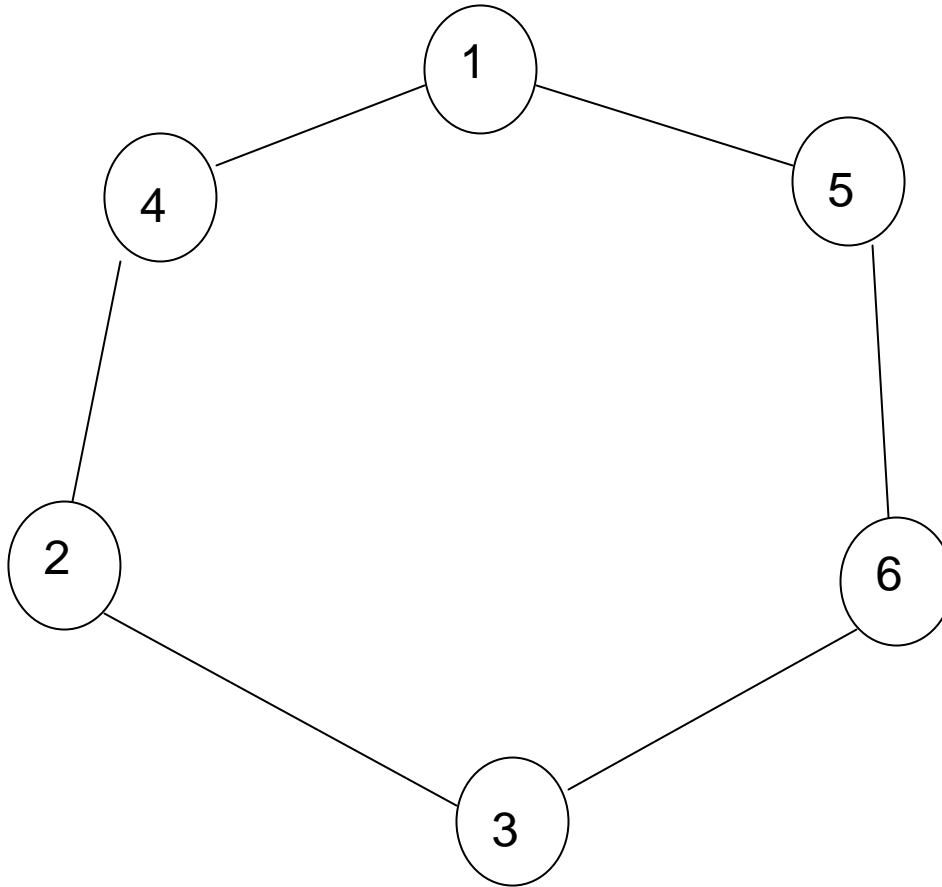
So if **any local algorithm** can be **emulated** by a canonic algorithm, the question remains:

How good can a canonic algorithm maximally be?

Rings

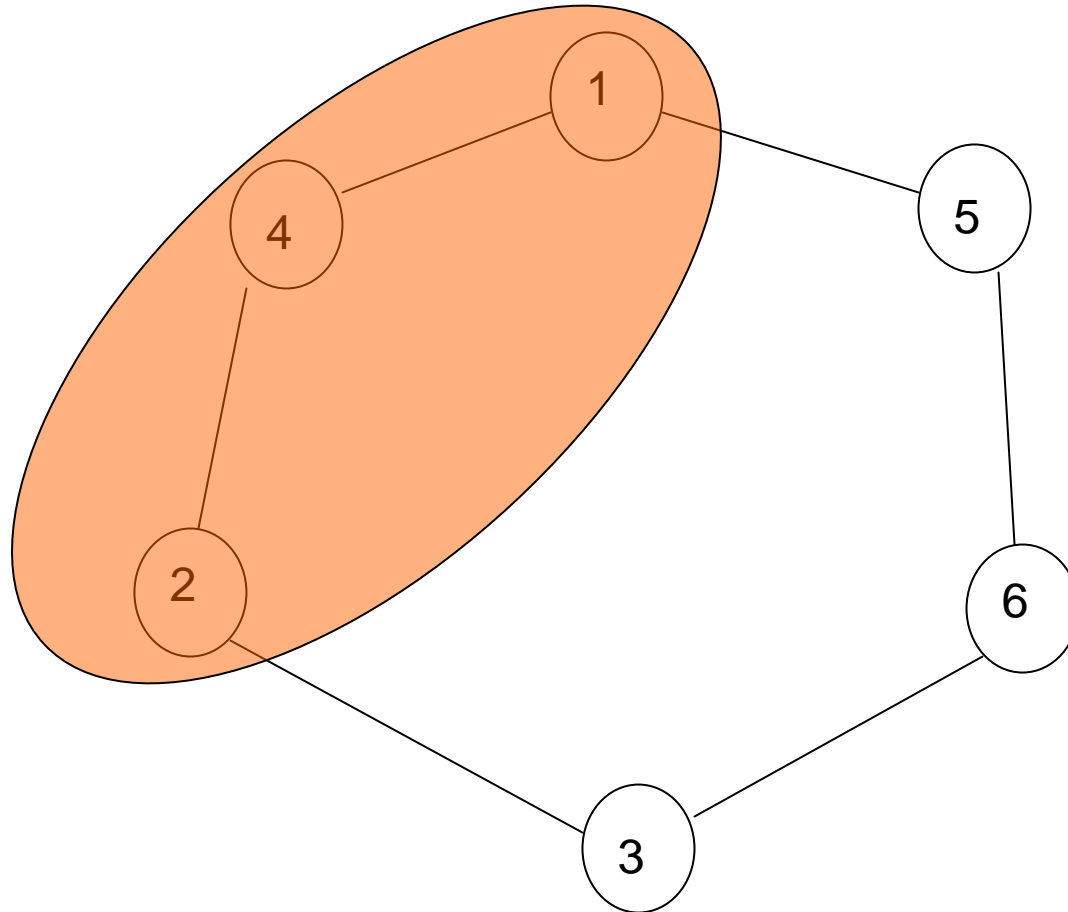
How do r-hop views of our rings look like?

E.g., 1-hop view of 4?



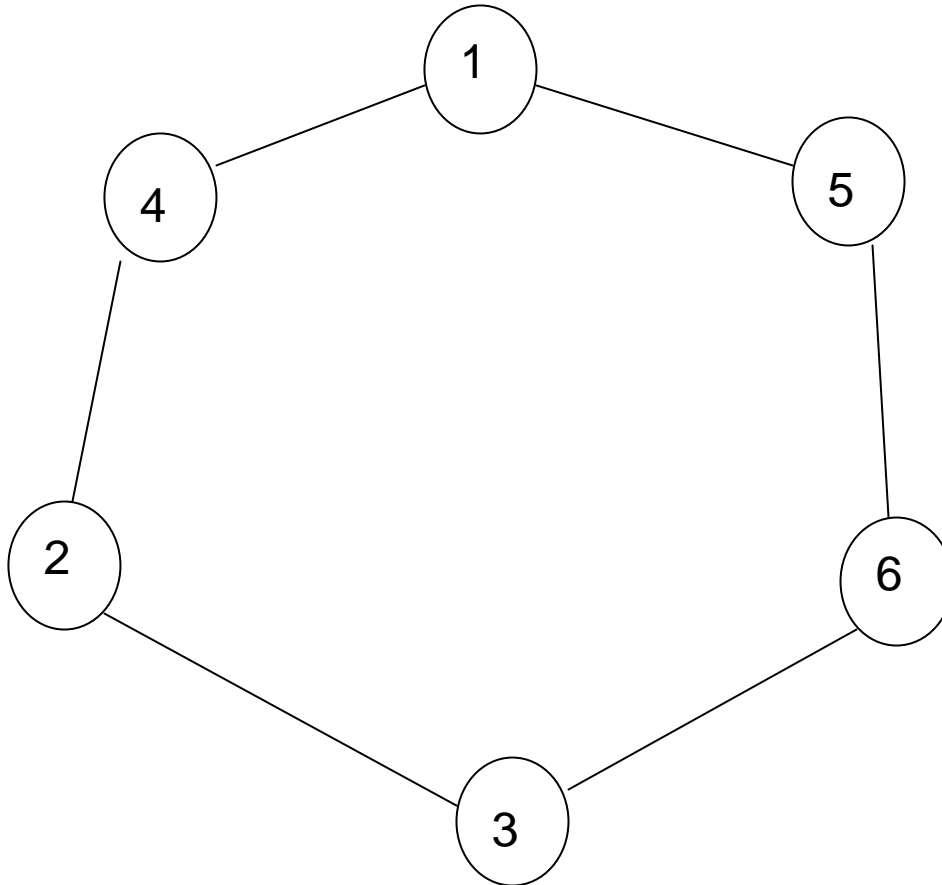
Rings

How do r-hop views of our rings look like?
E.g., 1-hop view of 4?



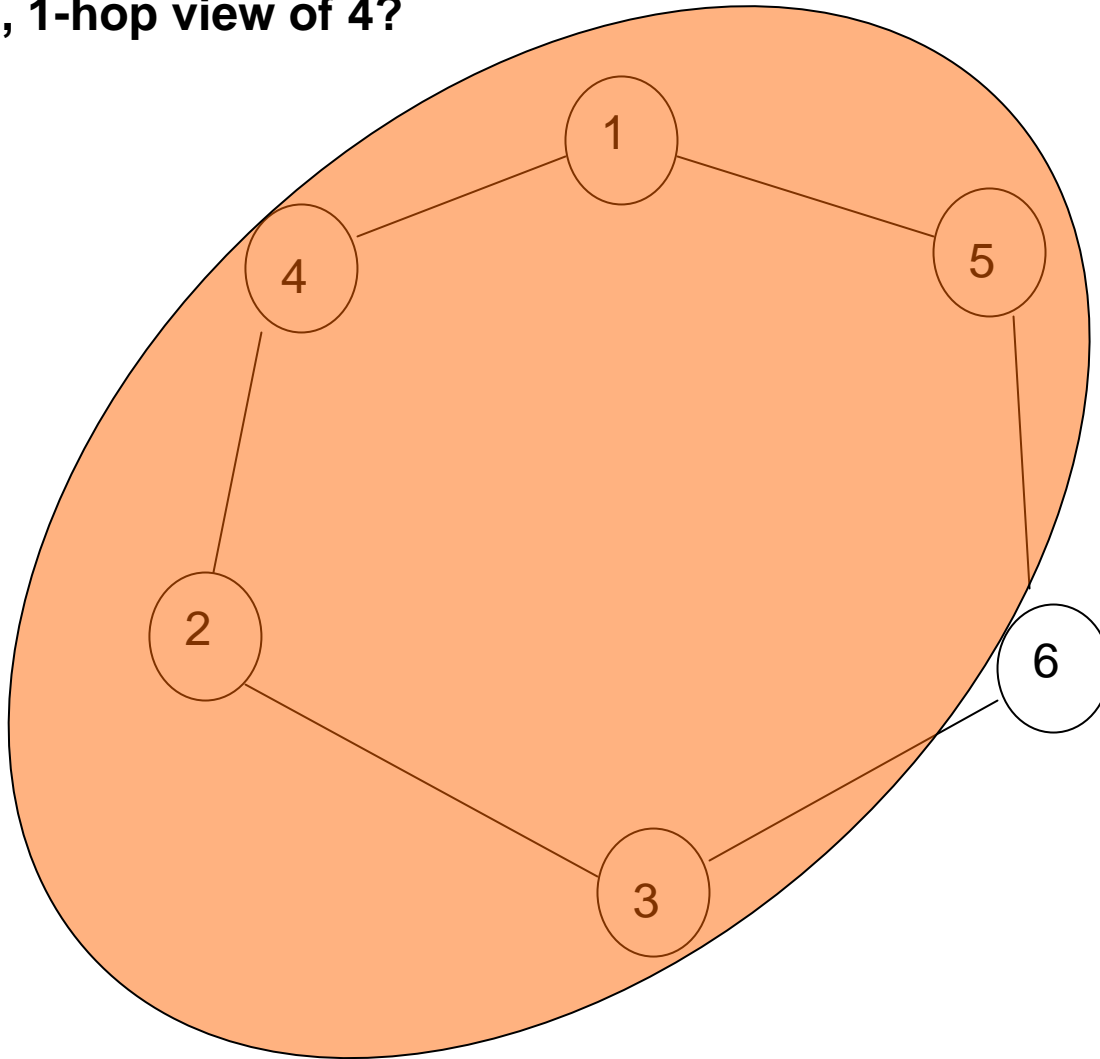
Rings

How do r-hop views of our rings look like?
E.g., 2-hop view of 4?



Rings

How do r-hop views of our rings look like?
E.g., 1-hop view of 4?



Ring Colorings

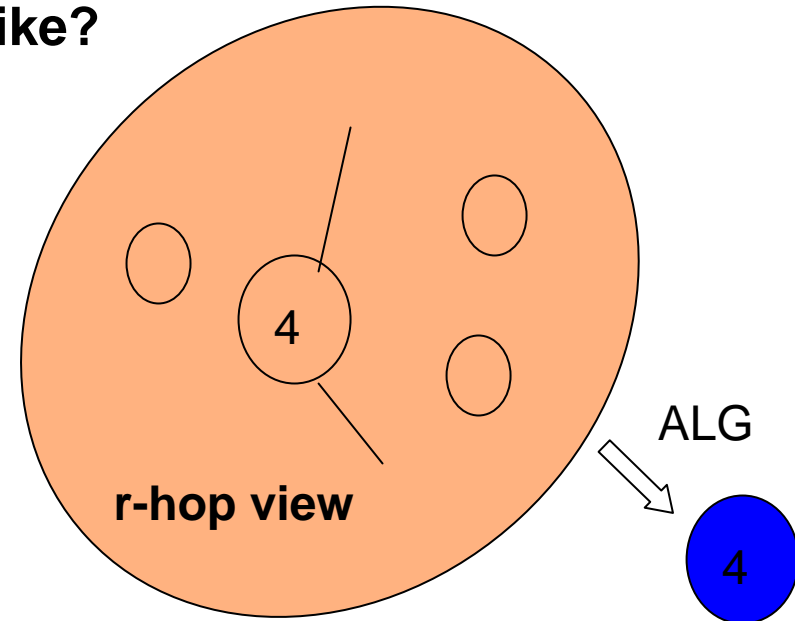
How do r -hop views of our rings look like?

Generally:

The r -hop view of a ring is a $(2r+1)$ tuple:

$$(l_{-r}, l_{-r+1}, \dots, l_0, \dots, l_r)$$

where l_0 is ID/label of considered node v .



A deterministic coloring algorithm maps these tuples to colors!

Question: why tuple and not set? Sense of orientation! 😊

Ring Colorings

When is a coloring valid?

Consider two r -hop views:

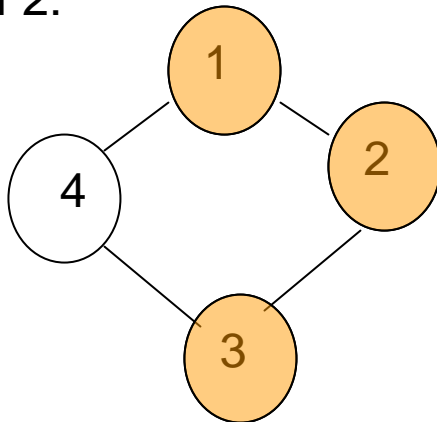
$$\begin{aligned} & (l_{-r}, l_{-r+1}, \dots, l_0, \dots, l_r) \\ \text{and} & \\ & (l'_r, l'_{r+1}, \dots, l'_0, \dots, l'_r) \end{aligned}$$

where $l'_i = l_{i+1}$ for $-r \leq i \leq r-1$ and $l'_r \neq l_r$ for $-r \leq i \leq r$, so what?

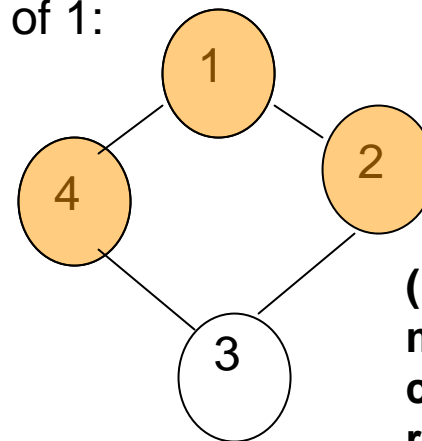
Then the two views can originate from adjacent nodes in the ring! So?

So every algorithm needs to assign different colors to the two views!

1-hop view of 2:



1-hop view of 1:



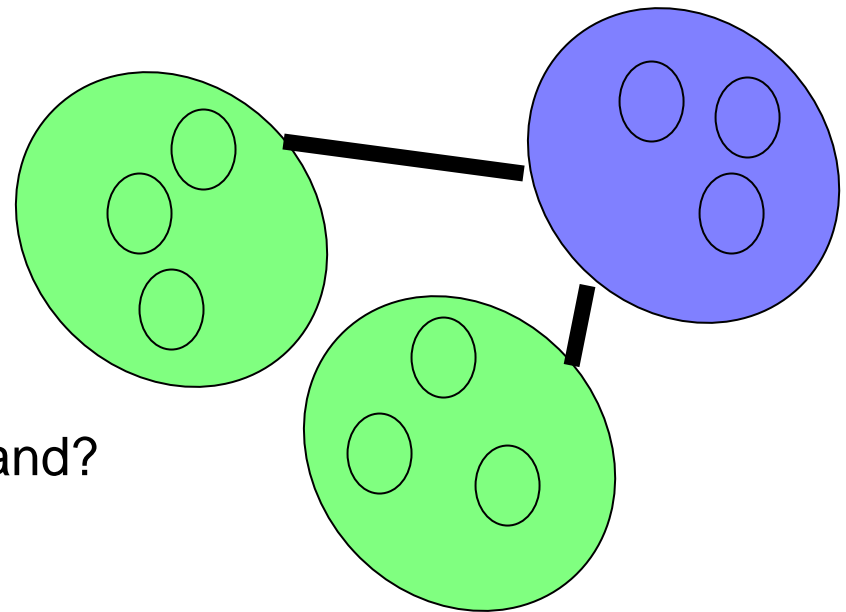
**(1,2,3) and (4,1,2)
must give different
colors (for 1 and 2,
respectively!)**

Neighborhood Graphs?

What if we define a **neighborhood graph**: neighborhoods are nodes, and connected if they are **conflicting** (i.e., views may originate from two adjacent nodes)?

Assume we **color the neighborhood graph** as follows: „view node“ has color of the node the neighborhood is computed from by deterministic local r-round algo.

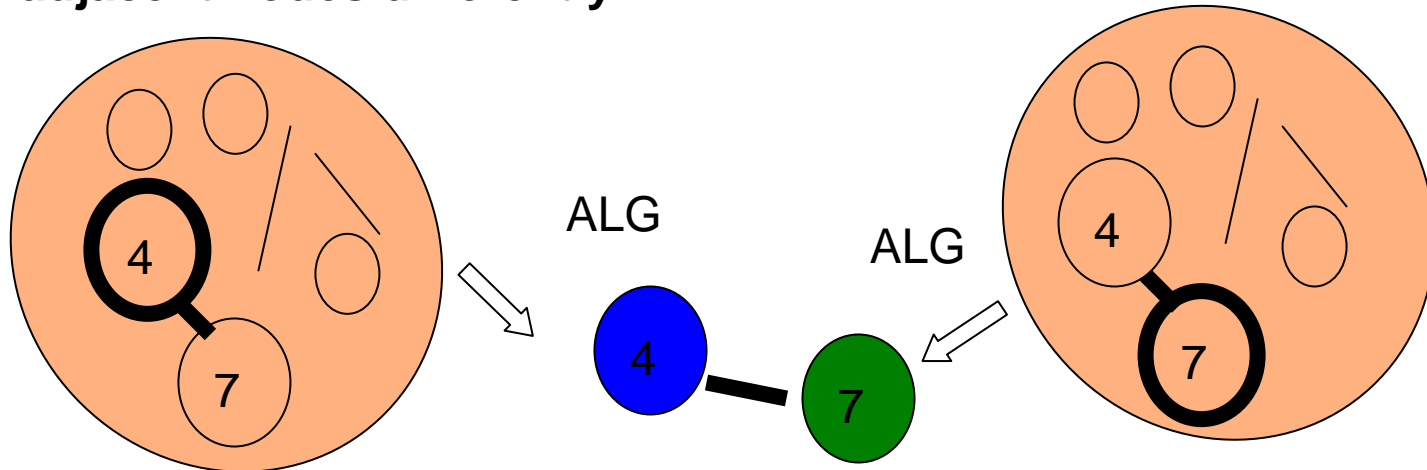
How does the coloring of the neighborhood graph look like then?



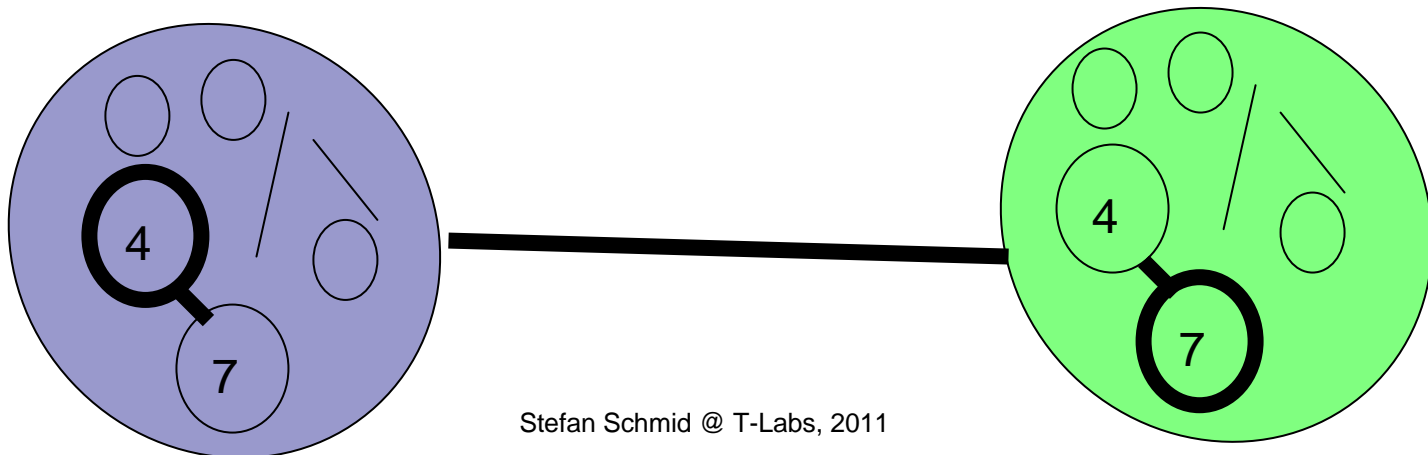
Same neighborhood = same color, and?

Neighborhood Graphs?

Given collected neighborhoods, canonic coloring ALG colors adjacent nodes differently:



So corresponding views/nodes in neighborhood graph must have different colors too, so **valid coloring for neighborhood graph**:



Neighborhood Graph

„Formal“ definition:

Neighborhood Graph

The **r-neighborhood graph** $N_r(G)$ consists of all r-hop views of G (for all nodes) which are connected iff they could originate **from two adjacent nodes**.

This lemma motivates the concept:

Lemma

There is an **r-round algorithm** that colors graphs G with c colors iff the chromatic number of the neighborhood graph is $\chi(N_r(G)) \leq c$.

Proof?

Neighborhood Graph

Lemma

There is an **r-round algorithm** that colors graphs G with c colors iff the chromatic number of the neighborhood graph is $\chi(N_r(G)) \leq c$.

Proof:

Because r-round algorithm defines **legal coloring on neighborhood graph!**
(Everything else could yield conflict: neighborhood graph contains all possible conflicts.)

We know: local coloring algo is a **function that maps r-hop view to color**, so to every node of $N_r(G)$...

This coloring is **legal**: by the definition of r-hop neighborhood graphs, adjacent nodes of $N_r(G)$ must have **different colors**, since the corresponding nodes in the underlying graph are also adjacent.
(But maybe slightly more than c colors are needed, so " \leq "...)

QED

**So how do neighborhood graphs of rings look like?
How to color them? And how to exploit the lemma
to get a lower bound?**

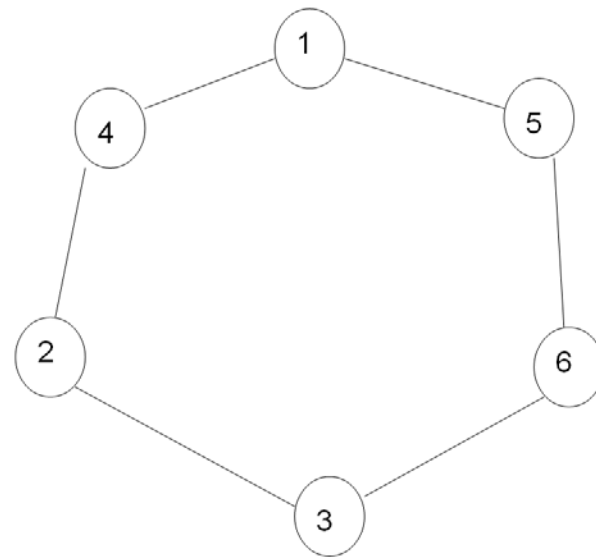
Roadmap

How to find a **good lower bound** with this lemma?

**We have to show that $\chi(N_r(G))$
is small only for a large r ...**

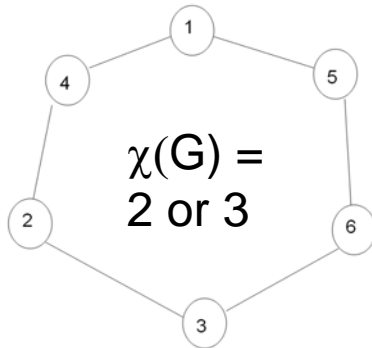
So how does $N_r(G)$ of a ring look like?

For example of our initial ring graph?

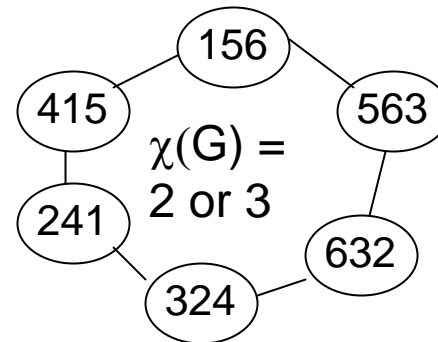


$N_r(\text{Given Ring})?$

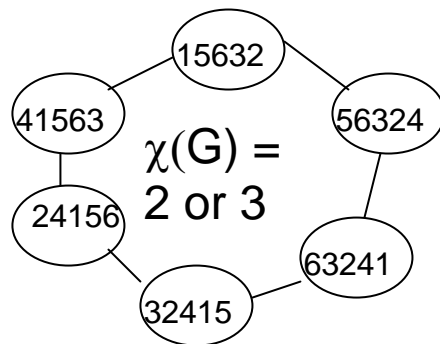
0-hop neighborhood graph?



1-hop neighborhood graph?



2-hop neighborhood graph?



So **0 or 1 round to 3-color**?!?

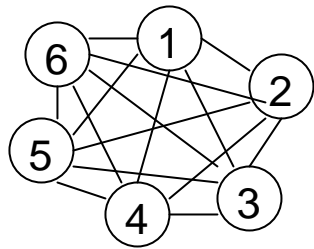
Attention: We are interested in neighborhood graphs of **families of graphs** / rings!

A given graph is easy (neighborhoods trivial)! 😊

$N_r(\text{Ring})?$

r-hop neighborhood graph for **ring family** (n=6 known)?

$N_0 = ?$

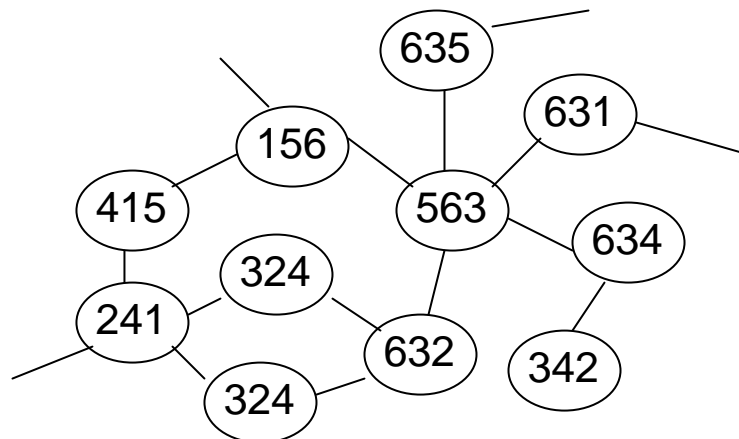


Complete graph: every node could be neighbor of every other node

$$\chi(N_0) = ?$$
$$= n$$

Any 0-local algorithm can only choose its ID as a color...: **n colors**

$N_1 = ?$



$$\chi(N_1) = ???$$

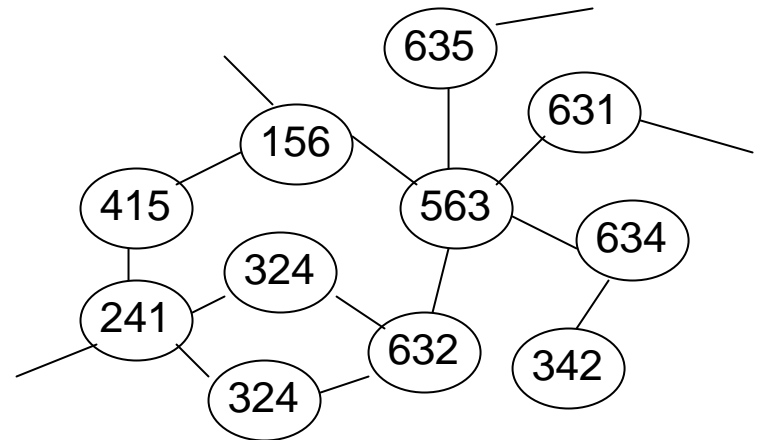
Not easy although quite regular...

$N_r(\text{Ring})?$

What happens for larger neighborhoods?

Intuitively, the larger the considered neighborhood, the **less conflicts** are possible! Chromoatic number declines for larger r ... (We will see: in **logarithmically** „per hop“!)

At some point, the graph family member is clear!

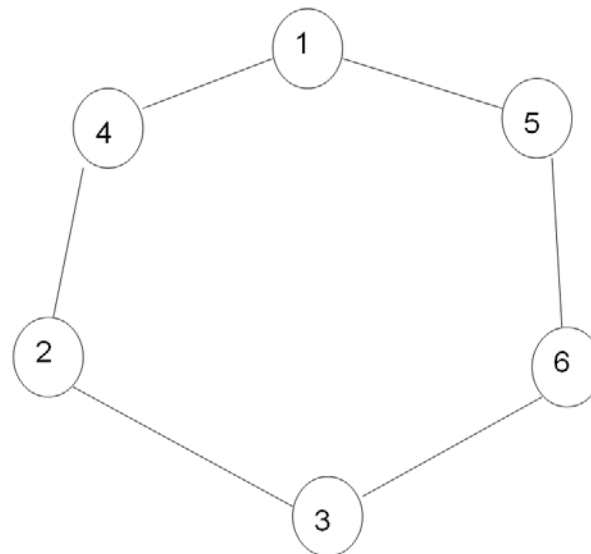


Main question now: What is $\chi(N_r(\text{Ring}))$??

Difficult... So let's focus on a graph which is **similar**, but has **less conflicts** and hence its chromatic number can be used instead for the **lower bound**!

What graphs are good then?

E.g., **subgraphs**...:
less conflicts, so
weaker lower bound
when applying our
lemma!



Neighborhood Graph of Ring

Instead of defining neighborhood graphs for rings:

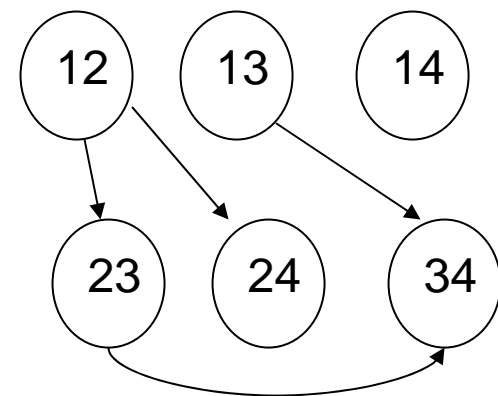
$B_{k,n}$ Graph

Assume two integers k, n where $n \geq k$. The $B_{k,n}$ graph consists of the nodes of k -tuples of increasing node labels (from $\{1, \dots, n\}$). There is a directed edge from node α to node β iff $\forall i \in \{1, \dots, k-1\}: \beta_i = \alpha_{i+1}$.

Example: $k=2, n=4$

$$\begin{aligned} V(B_{k,n}) &= ? \\ &= \{(1,2), (1,3), (1,4), (2,3), (2,4), (3,4)\} \end{aligned}$$

$$\begin{aligned} E(B_{k,n}) &= ? \\ &= \{((1,2), (2,3)), ((2,3), (3,4)), \\ &\quad ((1,2), (2,4)), ((1,3), (3,4))\} \end{aligned}$$



Neighborhood Graph of Ring

What does this have to do with rings?!

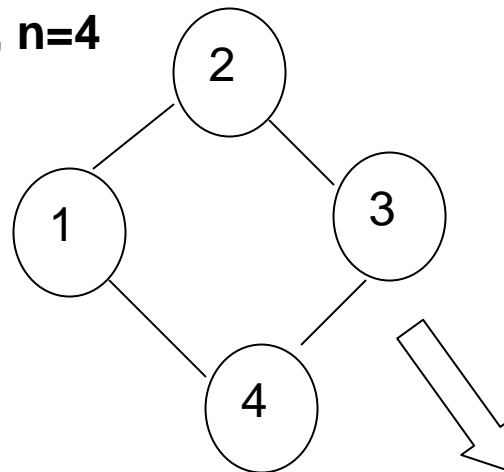
Lemma

Viewed as an **undirected** graph, $B_{2r+1,n}$ is a **subgraph** of the r -neighborhood graph of n -node rings with node labels from $\{1, \dots, n\}$.

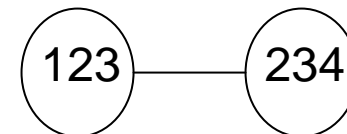
Example: Neighborhood $r=1$ (so $k=3$), $n=4$

$$\begin{aligned} V(B_{k,n}) &= ? \\ &= \{(1,2,3), (1,2,4), \\ &\quad (1,3,4), (2,3,4)\} \end{aligned}$$

$$\begin{aligned} E(B_{k,n}) &= ? \\ &= \{(1,2,3), (2,3,4)\} \end{aligned}$$



**Indeed!
Neighborhood
of 2 and 3!
But only a
subgraph! (Why?)**



Neighborhood Graph of Ring

Lemma

Viewed as an **undirected** graph, $B_{2r+1,n}$ is a **subgraph** of the r -neighborhood graph of n -node rings with node labels from $\{1, \dots, n\}$.

Proof?

The set of k -tuples of increasing labels is a **subset of all the k -tuples / nodes** (in our example, views of node 1 and 4 are missing).

Two nodes are only connected in $B_{2r+1,n}$ if **there is also an edge in the neighborhood graph** (because labels are ordered, the views must come from adjacent nodes): not more edges/conflicts.

What does it mean?!

QED

Chromatic number of $B_{2r+1,n}$ good for lower bound of our problem!

- We have to compute **lower bound for $\chi(B_{2r+1,n})!$**
- How? With another **helper graph**... 😊

Helper Graph

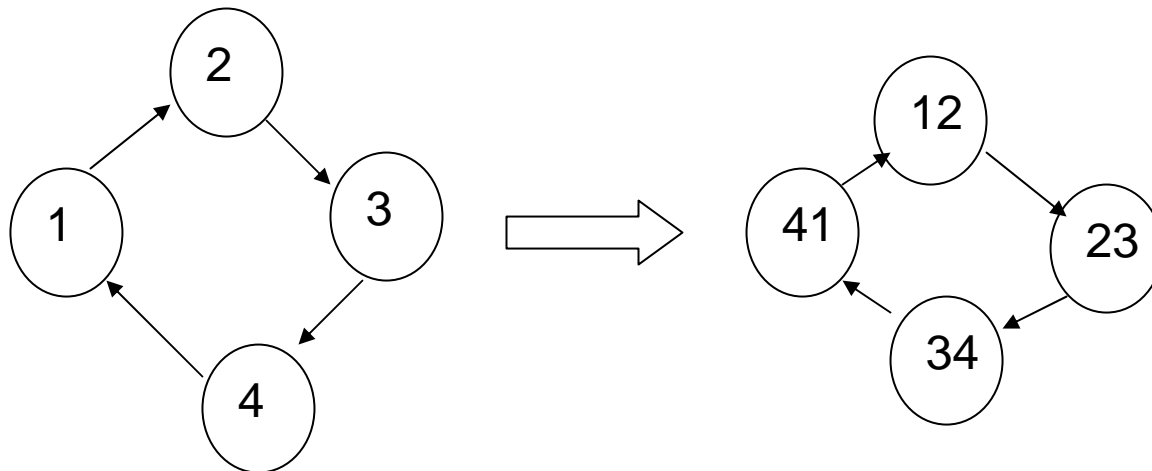
The following graph is helpful to analyze $B_{2r+1,n}$: What does it mean?

Diline Graph

The directed line graph (diline graph) $DL(G)$ of a directed graph $G=(V,E)$ is defined as follows: $V(DL(G))=E$, and there is a directed edge $((w,x),(y,z))$ iff $x=y$.

In other words: $DL(G)$ consists of the node representing the edges of G , and two nodes are connected if the corresponding edges „follow“ after each other.

Example:



What is the relation to $B_{k,n}$?!

Recursive Construction

$B_{k,n}$ can be **recursively defined** by directed line graphs!

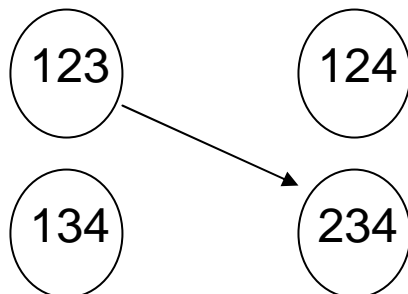
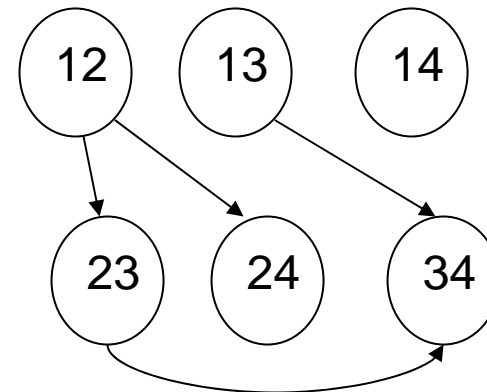
Lemma

$$B_{k+1,n} = DL(B_{k,n})$$

Really? Example: $k=2, n=4$?

$$V(B_{k,n}) = \{(1,2), (1,3), (1,4), (2,3), (2,4), (3,4)\}$$

$$E(B_{k,n}) = \{((1,2), (2,3)), ((2,3), (3,4)), ((1,2), (2,4)), ((1,3), (3,4))\}$$



Example: $k=3, n=4$?

$$V(B_{k,n}) = \{(1,2,3), (1,2,4), (1,3,4), (2,3,4)\}$$

$$E(B_{k,n}) = \{((1,2,3), (2,3,4))\}$$

Recursive Construction

$B_{k,n}$ can be **recursively defined** by directed line graphs!

Lemma

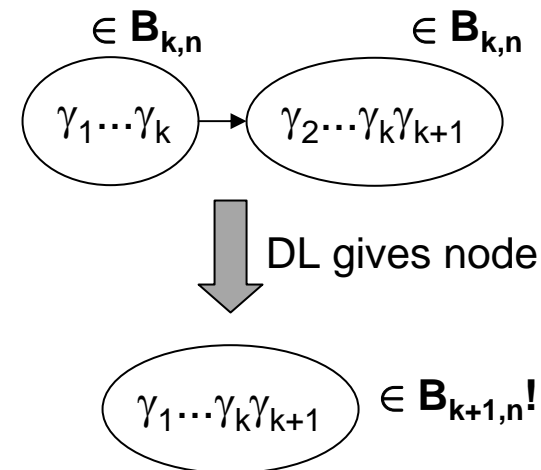
$$B_{k+1,n} = DL(B_{k,n})$$

Proof?

By the definition of $B_{k,n}$, two nodes α, β are connected if the first $k-1$ labels in β are the same as the last $k-1$ labels of α .

Therefore, the pair (α, β) can be represented by a $(k+1)$ tuple $\gamma = (\gamma_1, \dots, \gamma_{k+1})$ with $\gamma_1 = \alpha_1$, $\gamma_i = \beta_{i-1} = \alpha_i$ for $2 \leq i \leq k$, and $\gamma_{k+1} = \beta_k$. The labels of γ are increasing too! So $B_{k+1,n}$ has the **same node set** as $DL(B_{k,n})$.

What about the edges?



Recursive Construction

$B_{k,n}$ can be **recursively defined** by directed line graphs!

Lemma

$$B_{k+1,n} = DL(B_{k,n})$$

Proof (continued for edges...)

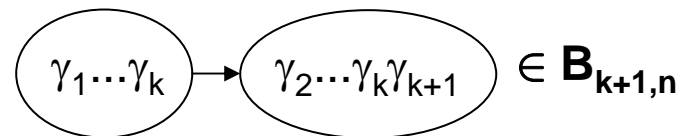
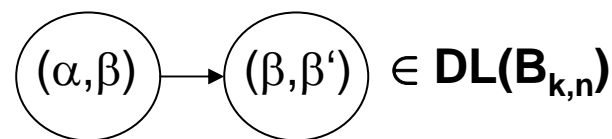
There is an edge between two nodes

(α, β) and (α', β') of $DL(B_{k,n})$ if $\beta = \alpha'$.

This is equivalent to that the two corresponding $(k+1)$ -tuples γ and γ' are neighbors in $B_{k+1,n}$:

the last k labels of γ are equivalent to the first k labels of γ' .

QED



So, $B_{k,n}$ graphs are simply „iterated line graphs“!

Chromatic Numbers

Holds for general graphs G !

Implication for colorings,
coloring G vs $DL(G)$?

Proof idea?

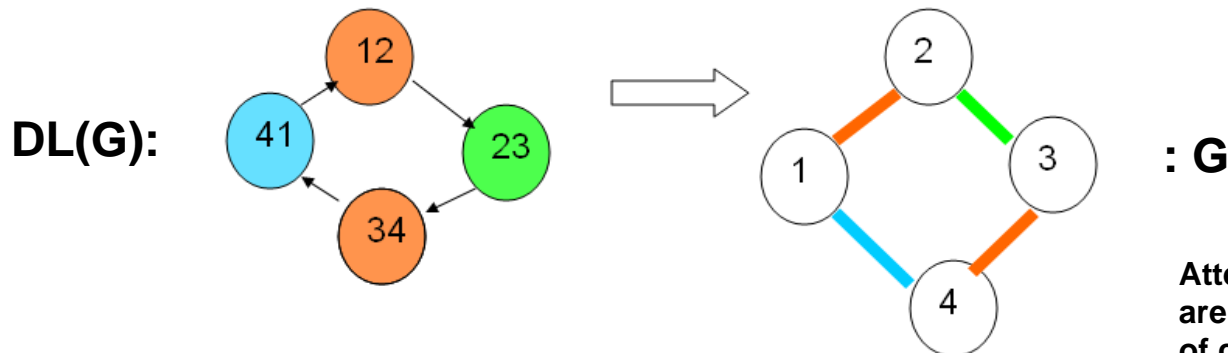
Lemma

$$\chi(DL(G)) \geq \log_2(\chi(G))$$

Given a c -coloring of $DL(G)$ we construct a **2^c coloring of G** (so minimal coloring of G can only be smaller).

How does coloring of G and $DL(G)$ relate?

Note: A c -coloring of the diline graph $DL(G)$ can be seen as a **coloring of the edges of G** such that no two adjacent edges have the same color (definition of $DL(G)$).



Attention: these graphs
are generally not rings
of course! ☺

Chromatic Numbers

Implication for colorings,
coloring G vs $DL(G)$?

Proof idea (continued...)

For a node $v \in G$, let S_v denote the set of colors of its outgoing edges in the graph. Let (u,v) be a directed edge in G and let x be the color of (u,v) .

Thus: $x \in S_u$.

No edge (v,w) can have color x , so $x \notin S_v$, so $S_u \neq S_v$: neighboring nodes in G must have **different „out-edge-color-sets“!**

We can use these color sets S to obtain a **vertex coloring of G** : the color of a node u is S_u . This coloring must be legal!

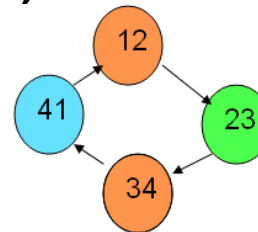
As we can have **at most 2^c subsets** (of c vertex colors of $DL(G)$ and hence edge colors of G), the coloring has at most 2^c colors.

QED

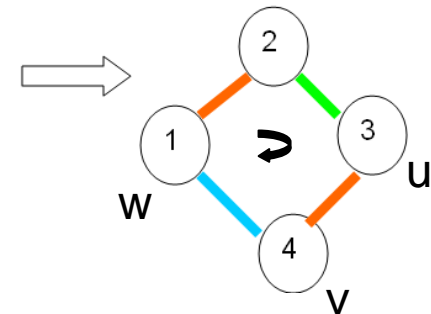
Lemma

$$\chi(DL(G)) \geq \log_2(\chi(G))$$

$DL(G)$:



G :



Chromatic Numbers

Chromatic number of $B_{k,n}$?

Recall: Gives lower bound for r-hop coloring algo!

Intuitively: Each time the local view is increased, the chromatic number goes down **at most by log!**

Lemma

$$\chi(B_{1,n}) = n \text{ and } \chi(B_{k,n}) \geq \log^{(k-1)} n$$

Proof idea?

$B_{1,n}$ is the complete graph.

For larger k , it holds by induction due to our lemmas!

QED

Finally: Lower Bound

Combining everything gives our lower bound! 😊

Lower Bound

Any deterministic distributed algorithm to color a ring with 3 or less colors needs at least $(\log^* n)/2 - 1$ rounds.

Proof idea?

We need to show that $\chi(B_{2^{r+1},n}) > 3$ for all $r < (\log^* n)/2 - 1$.

We know that $\chi(B_{2^{r+1},n}) \geq \log^{(2^r)} n$.

And $B_{2^{r+1},n}$ is **subgraph** of neighborhood graph we actually want!

The rest is simple maths...

QED

Literature for further reading:

- Peleg's book (as always 😊)

End of lecture