Learning with Deficient Supervision-II

CS771: Introduction to Machine Learning

Purushottam Kar

Announcements

- End sem examination: November 17, 1600-1900, L18,19,20, ERES
  - Open notes (handwritten only)
  - Please bring a pencil and eraser with you
  - Seating arrangement same as midsem – will announce again
- Project presentation schedule open for slot choice
  - 15 minute presentations for each group
  - Please choose a slot by November 18 1159 hrs
  - Please do not overwrite each other's slots
- Final project report due November 26 1159PM IST (premidnight)
  - No late submission deadline since grade submission is overdue by then
  - Please refer to Piazza post on how to write and structure your report

Recap

- We saw how label imbalance impacts classification problems
  - Binary, multi-class and multi-label
- For binary classification problems we saw three solutions
  - Resampling
    - Oversample rare class or undersample popular class
    - Not nice as either throws away data or bloats up training set
    - Not extendable to multi-class and multi-label settings elegantly
  - Reweighted learning
    - Assign different weights to point of different classes
    - Nicely extends to multi-class settings
  - Changing the evaluation/training loss function
    - F-measure, AUC etc
    - Algorithms more involved but the extra work does pay off!
- Today: learning with weak, active, and semi-supervision

Learning with Weak Supervision

Weak Supervision

Weak Supervision

- Refers to supervision at a high level

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- Related concepts – distant supervision, multi-instance learning

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Less effort to label

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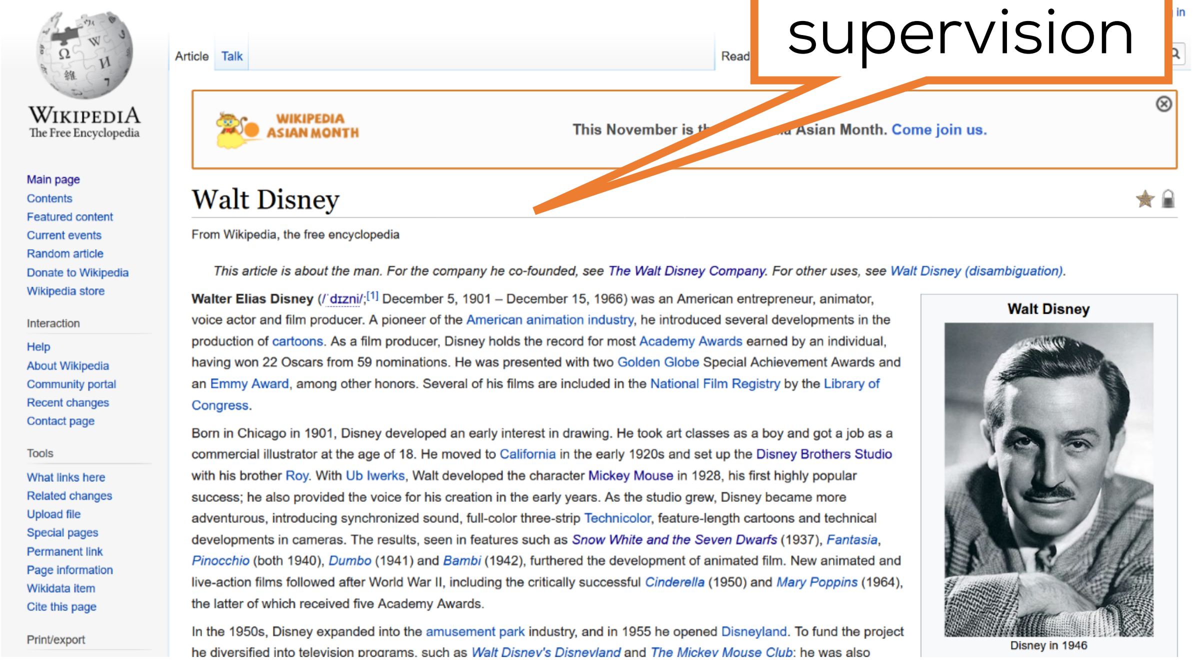

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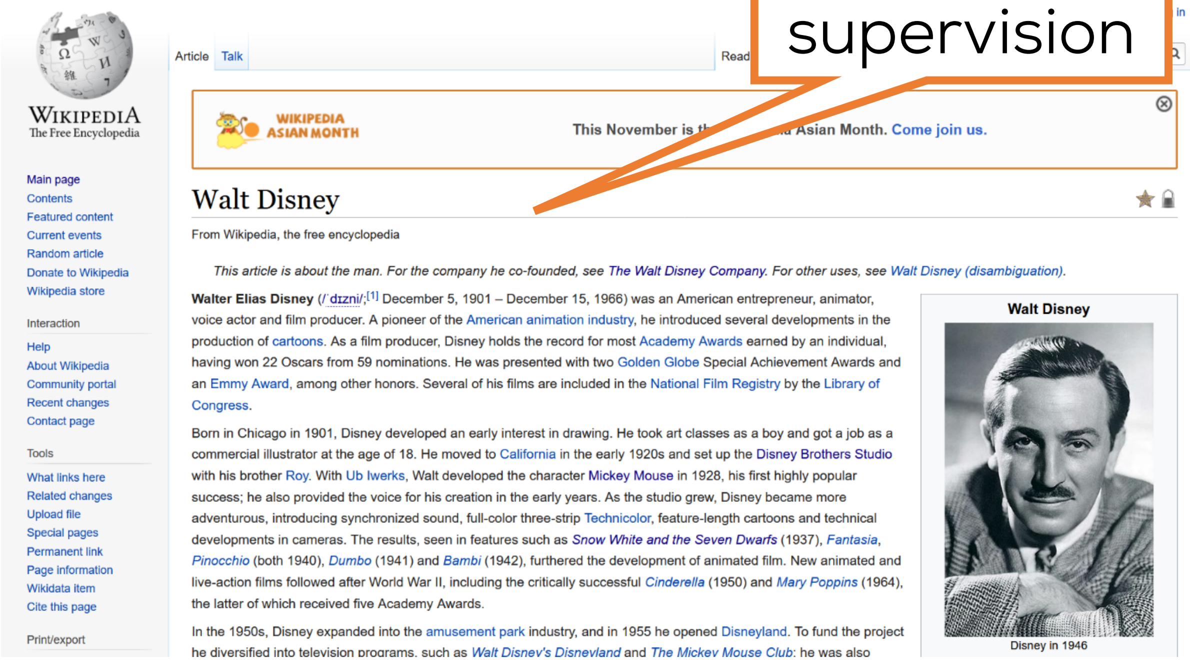

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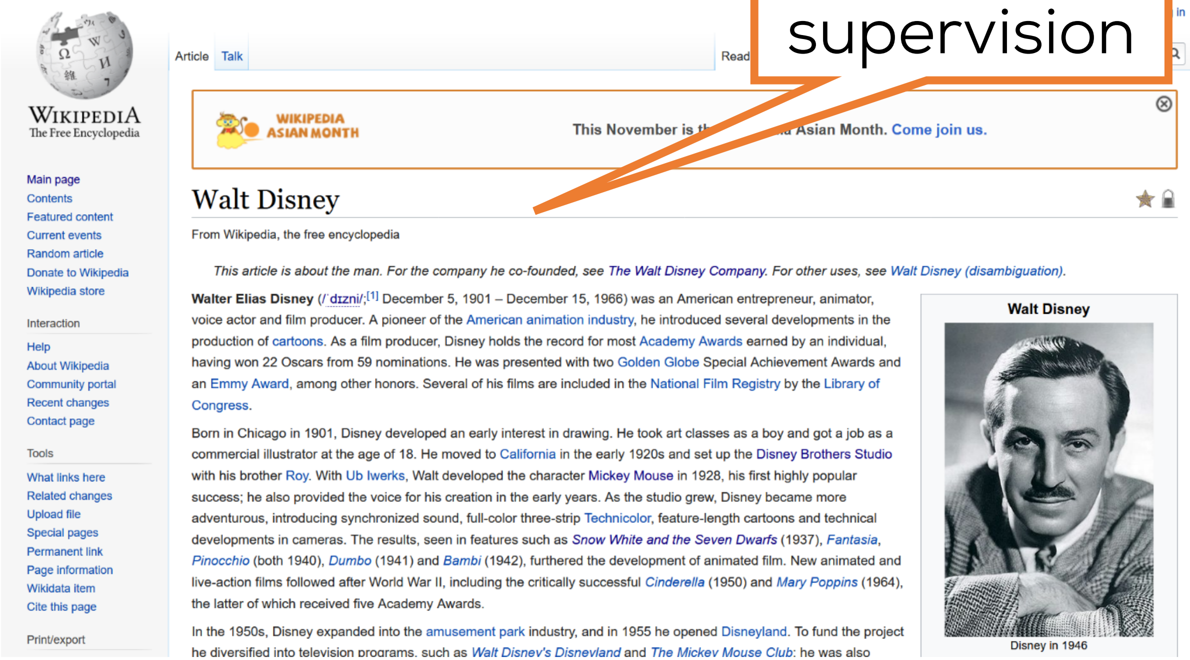
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- Relation extraction problem

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- Supervision at high level – distant superv., multi-instance learning
- **Multi-instance learning**: every data point is a "bag" of m "items"

$$x^i = \left\{x^{i,1}, x^{i,2}, \dots, x^{i,m}\right\}$$

  - Every possible bounding box is an item. Their collection is the image
  - Every sentence is an item. Their collection is the Wikipedia document
- The "bag" has a multi-label $\mathbf{y}^i \in \{0,1\}^L$
  - Labels in the image example could be man, horse, dog, cat, tree, river, …
  - A bit more tricky to define labels for relation extraction so skip it for now
- Not told which item(s) caused individual labels $\mathbf{y}_k^i$ to turn on or off
  - Which bounding box contains the dog?
  - Which sentence signals the relationship b/w Disney and Mickey?
- "Fine" supervision could have, for e.g., labelled every item in the bag

Solutions?

- Can often be elegantly cast as latent variable learning problems
- For every bounding box/sentence, latent vars. $z^{i,j,k}, j \in [m], k \in [L]$
- $z^{i,j,k} = +1$ if that item is of "interest" w.r.t. label k else $z^{i,j,k} = 0$
- Final label can be $\mathbf{y}_k^i = \mathrm{UNION}\left(z^{i,1,k}, z^{i,2,k}, \ldots, z^{i,m,k}\right)$
  - $\mathbf{y}_k^i = 1$ if any item declares that label to be present
  - Other "aggregation" techniques possible – ask at least 2 items to declare
- Learn models for joint inference of latent variables and final label
- Alternative is a two-stage process
  - First find item that are of interest i.e. for which $z^{i,j} \neq 0$
    - Use object detection techniques to find useful bounding boxes
    - Use entity detection techniques to find mentions
  - Label each interesting item and aggregate to get labels for bag

Active Learning

The active teacher

- The algorithm only gets unlabelled data points $S = \{x^1, \ldots, x^n\}$
- However, labels can be requested for $k \ll n$ points “on demand”
  - Need not ask all labels in a single go
  - Can ask for one label, process that, then ask for another label, and so on
- k must be small since most often, an actual human is involved
- We have only studied “passive” models till now where teacher retires after presenting the data
- Lots of techniques available for active learning
  - Most rely on some form of expected knowledge gain
  - Which unlabelled data point expected to surprise me the most?
  - Very “active” area (pun intended) – dedicated workshops at NIPS, ICML
  - Very useful in guiding consumer surveys - cannot have a lot of them!
  - Carefully choose which customers to entice into revealing more info

Active Learning Attempt I

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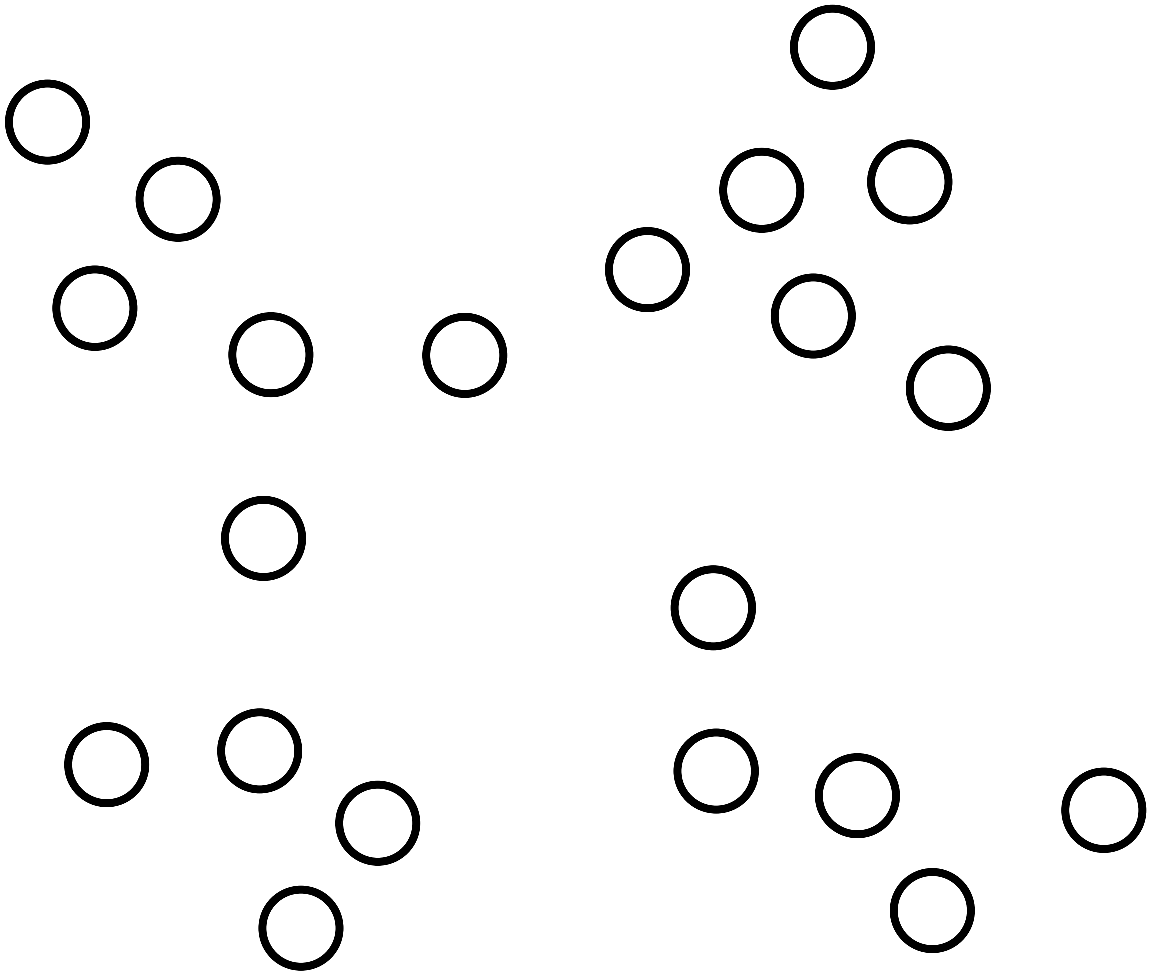

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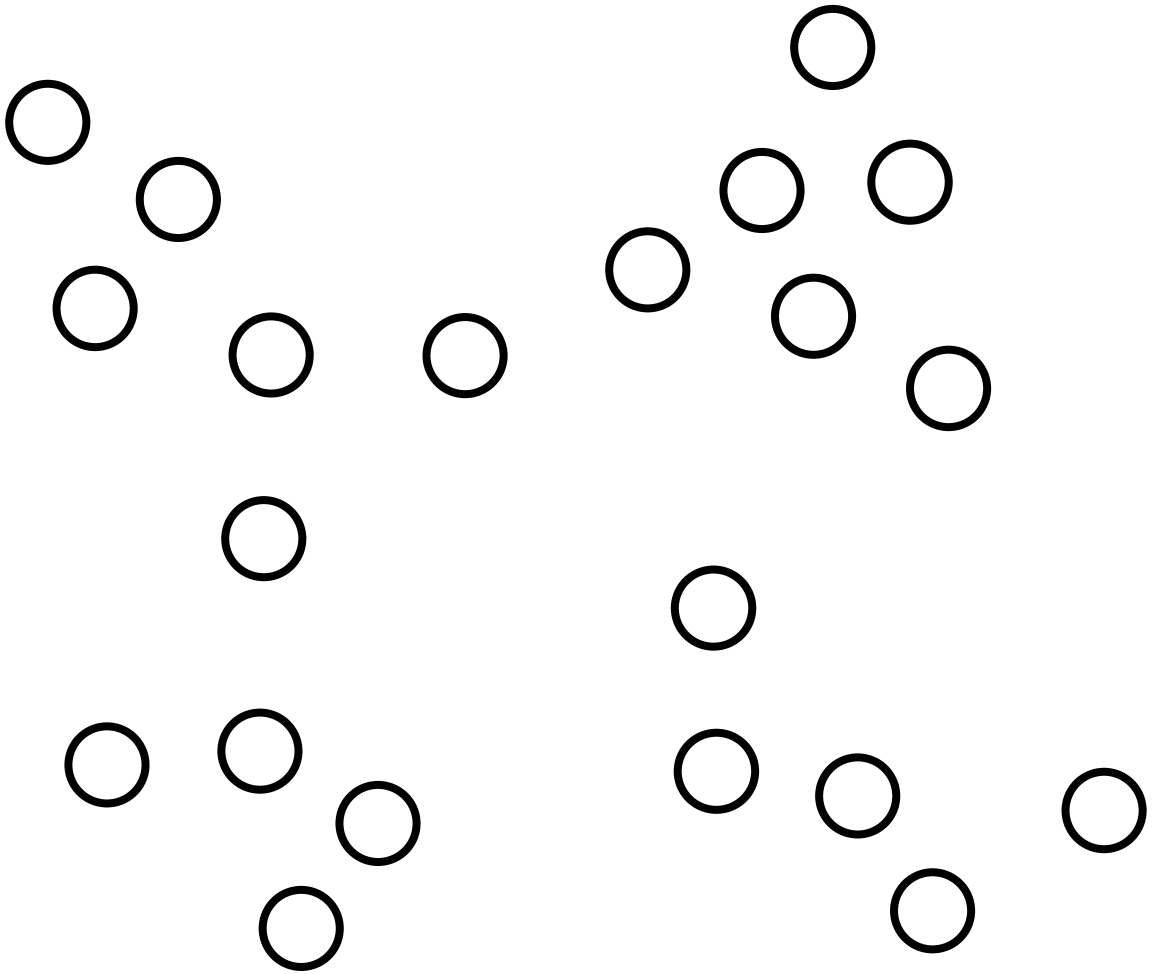

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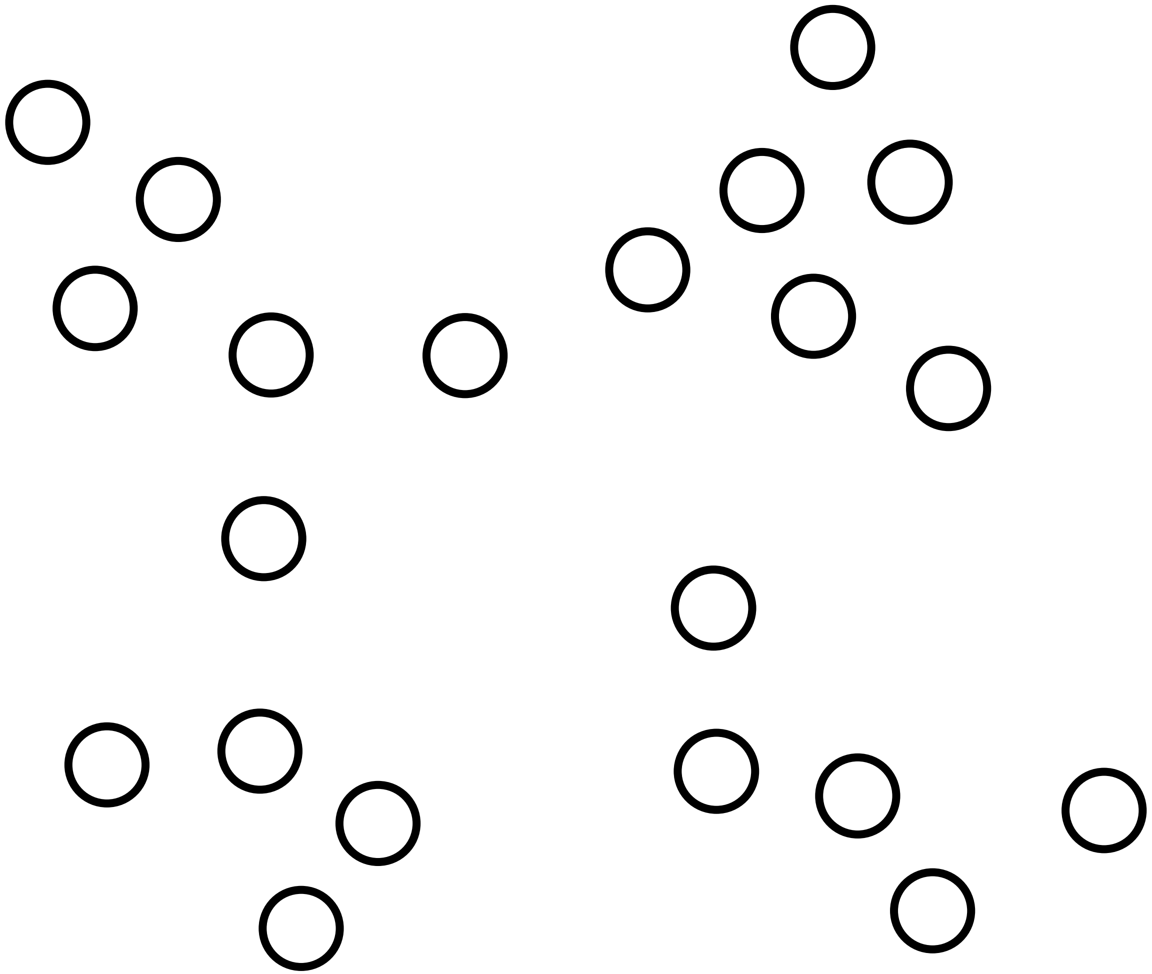

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- Apply clustering (k-means, agglomerative, kernel k-means)

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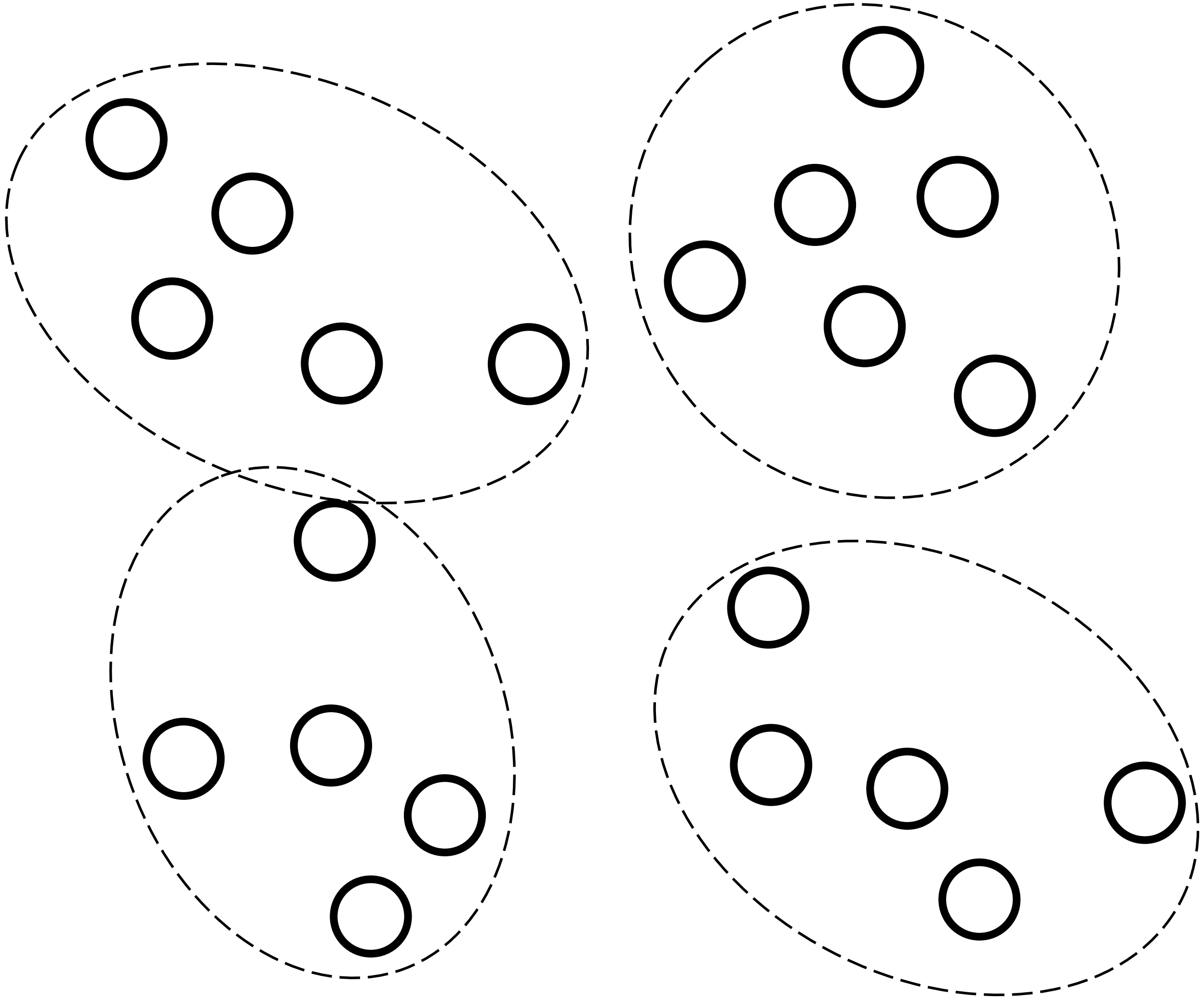

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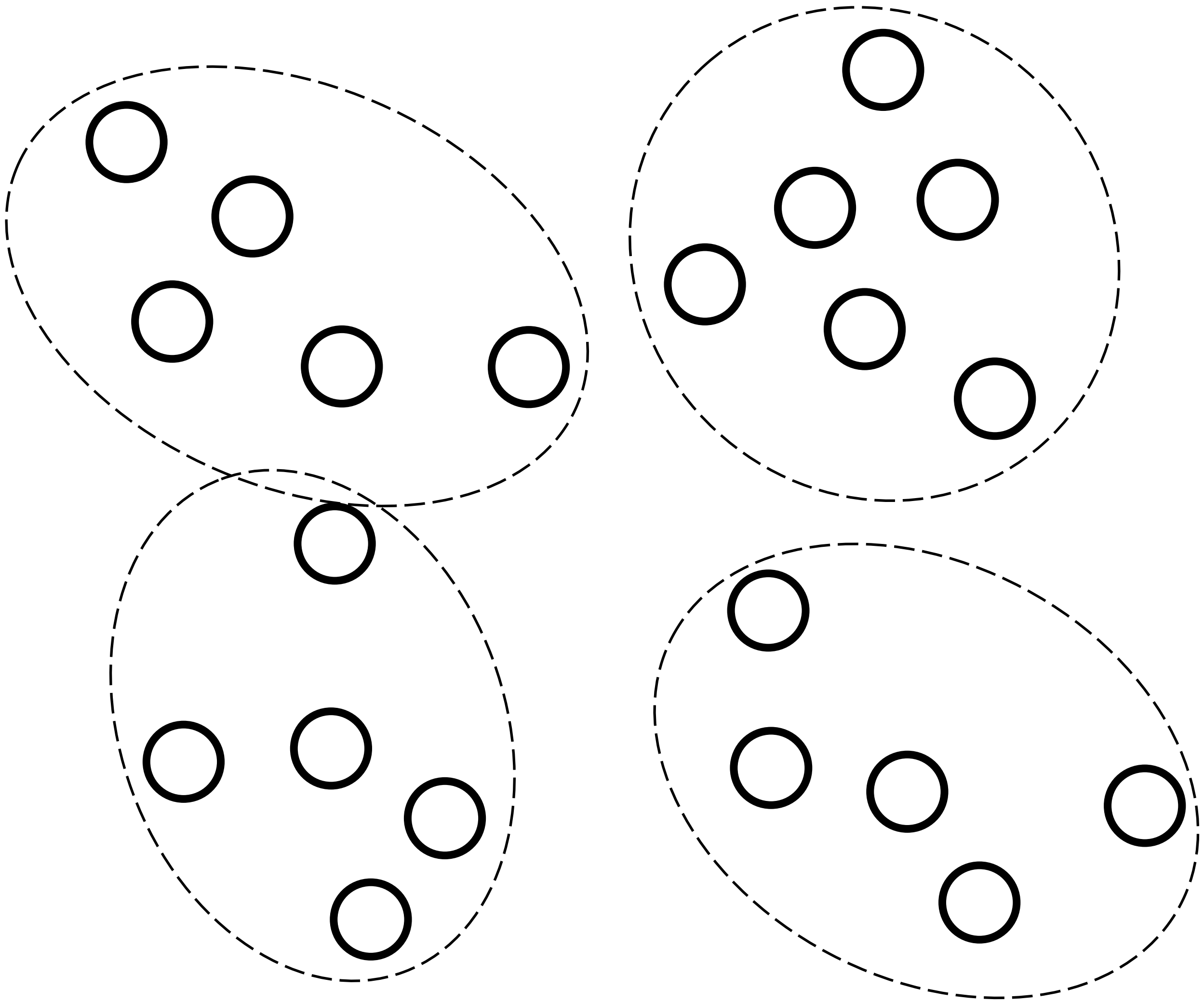

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- Choose one data point from each cluster and query its label

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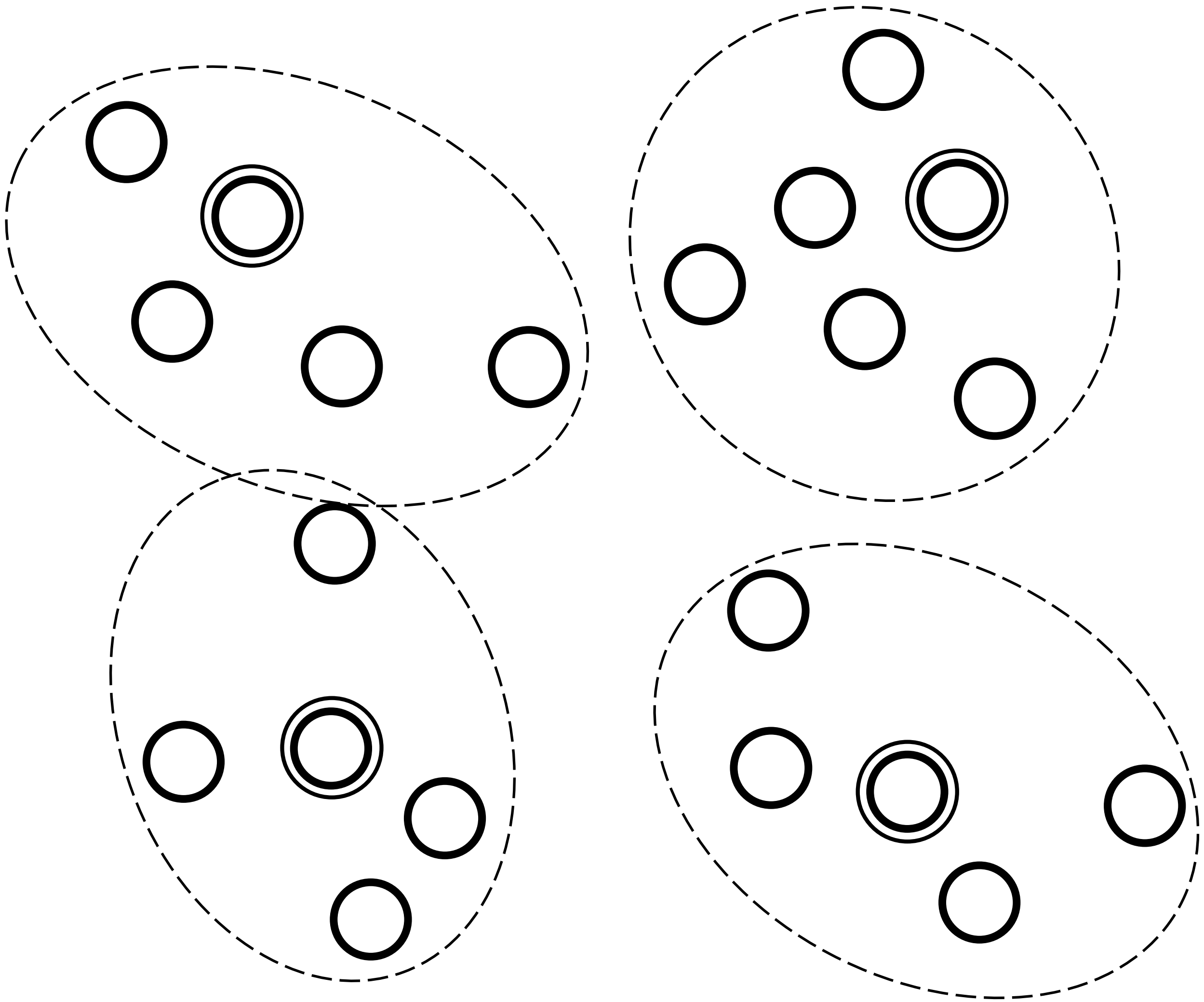

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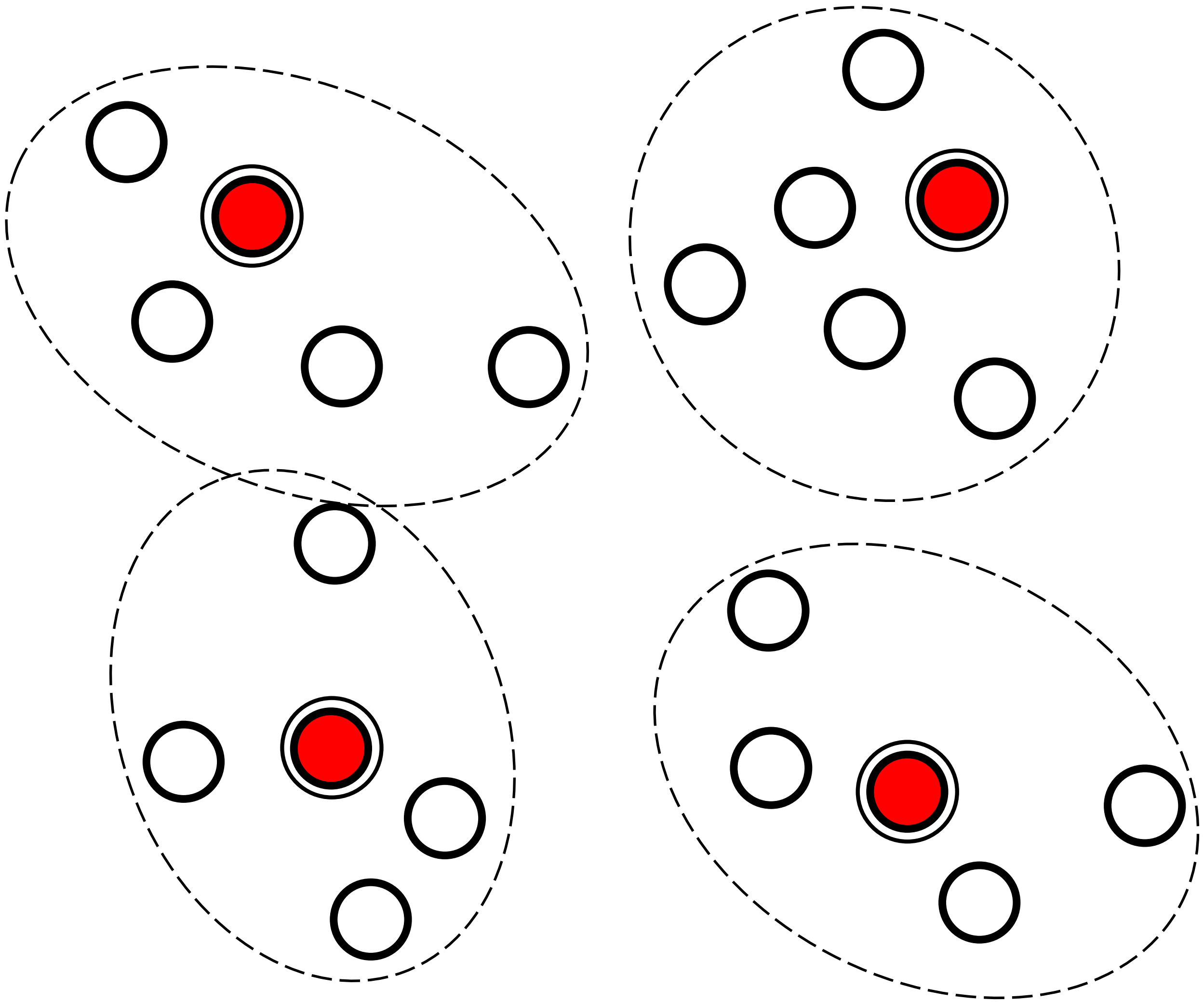

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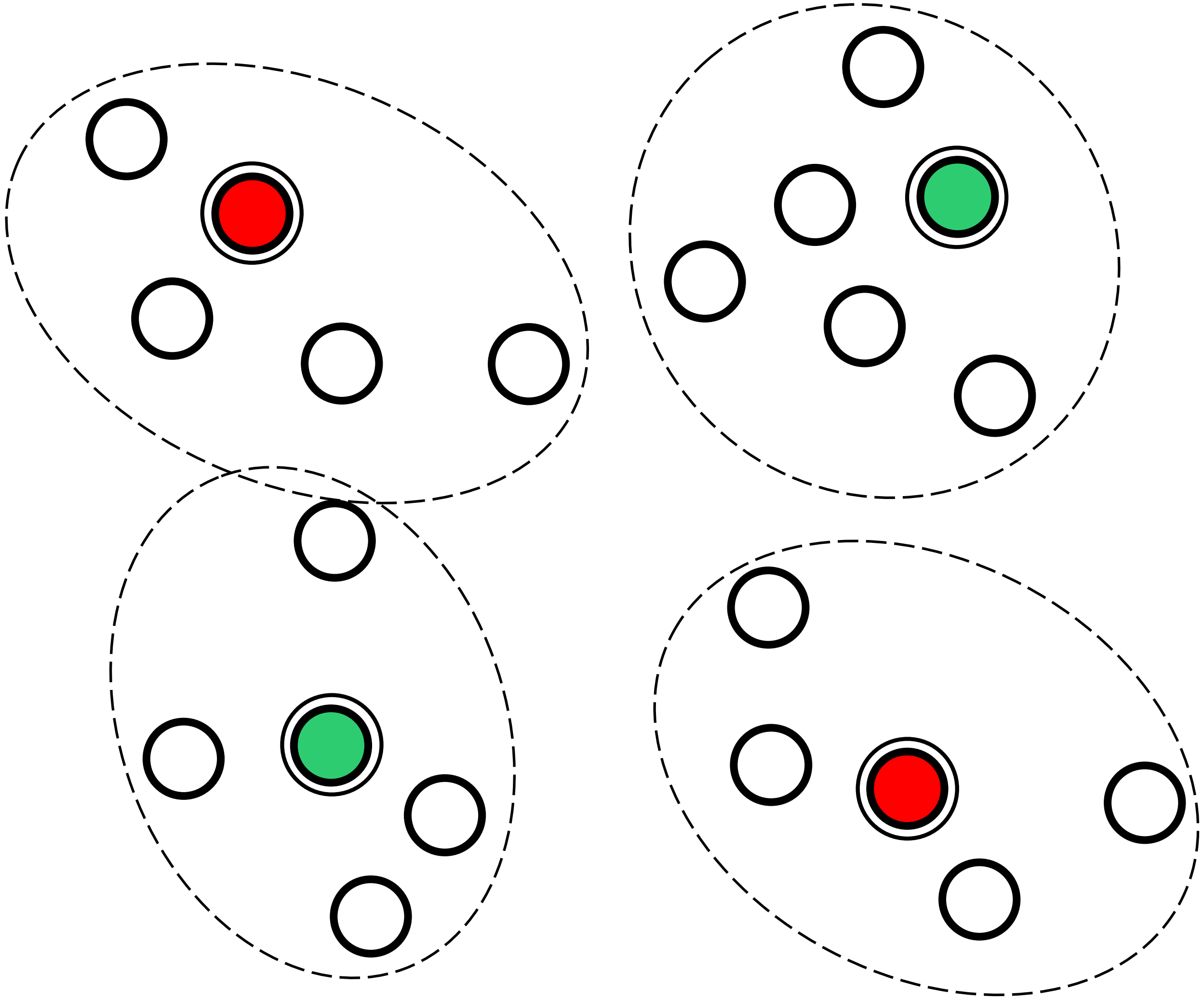

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- Label the cluster!

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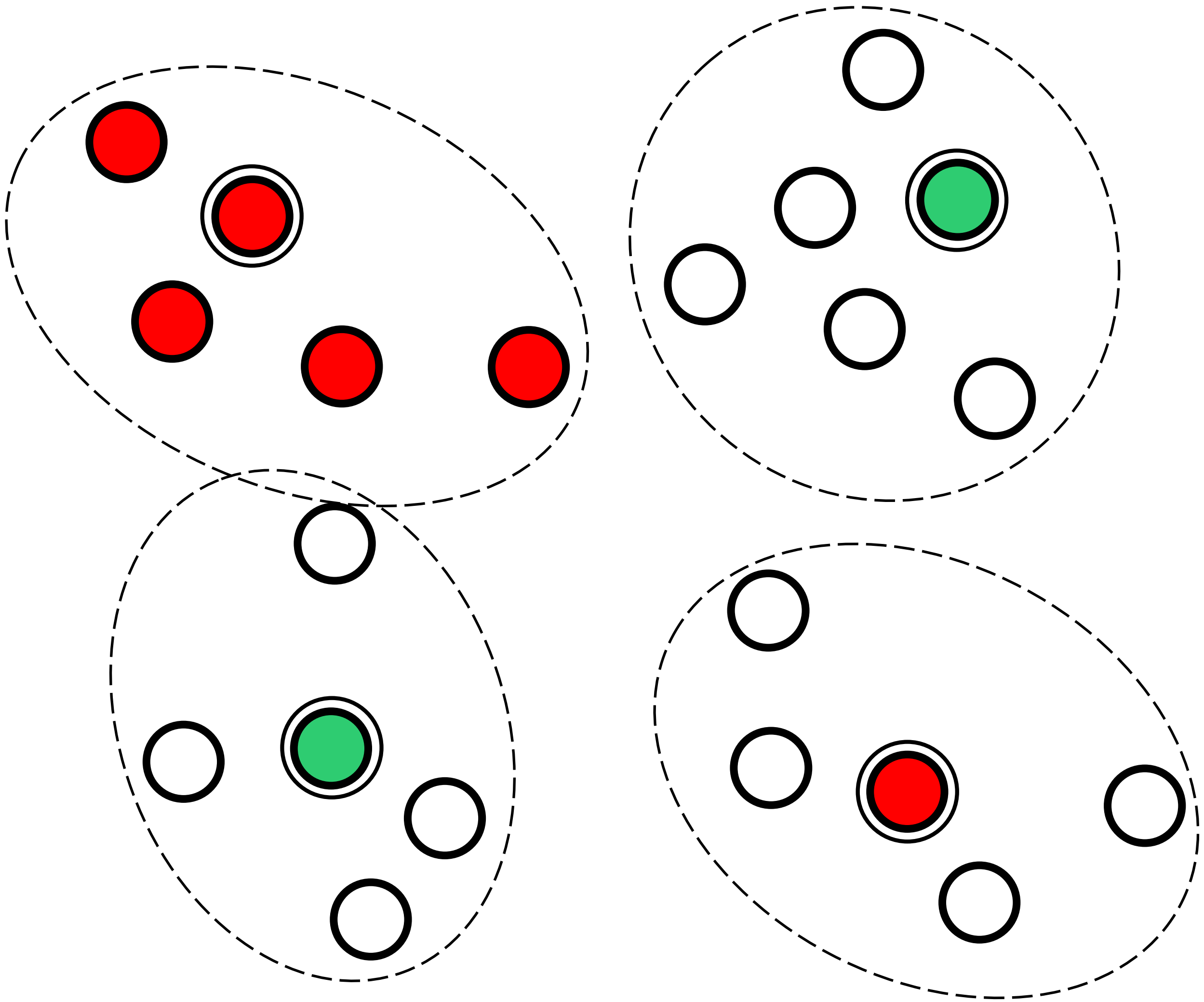

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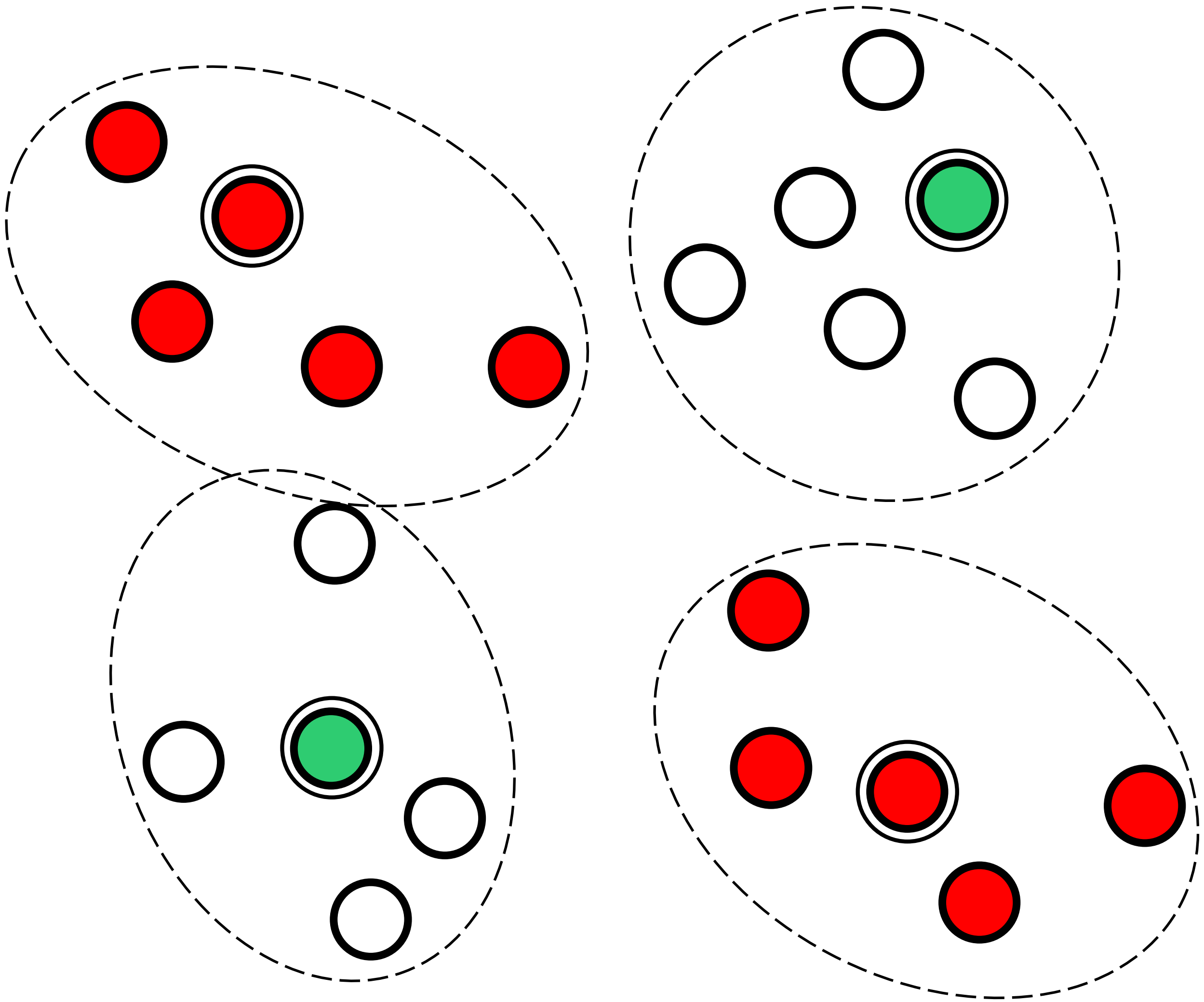

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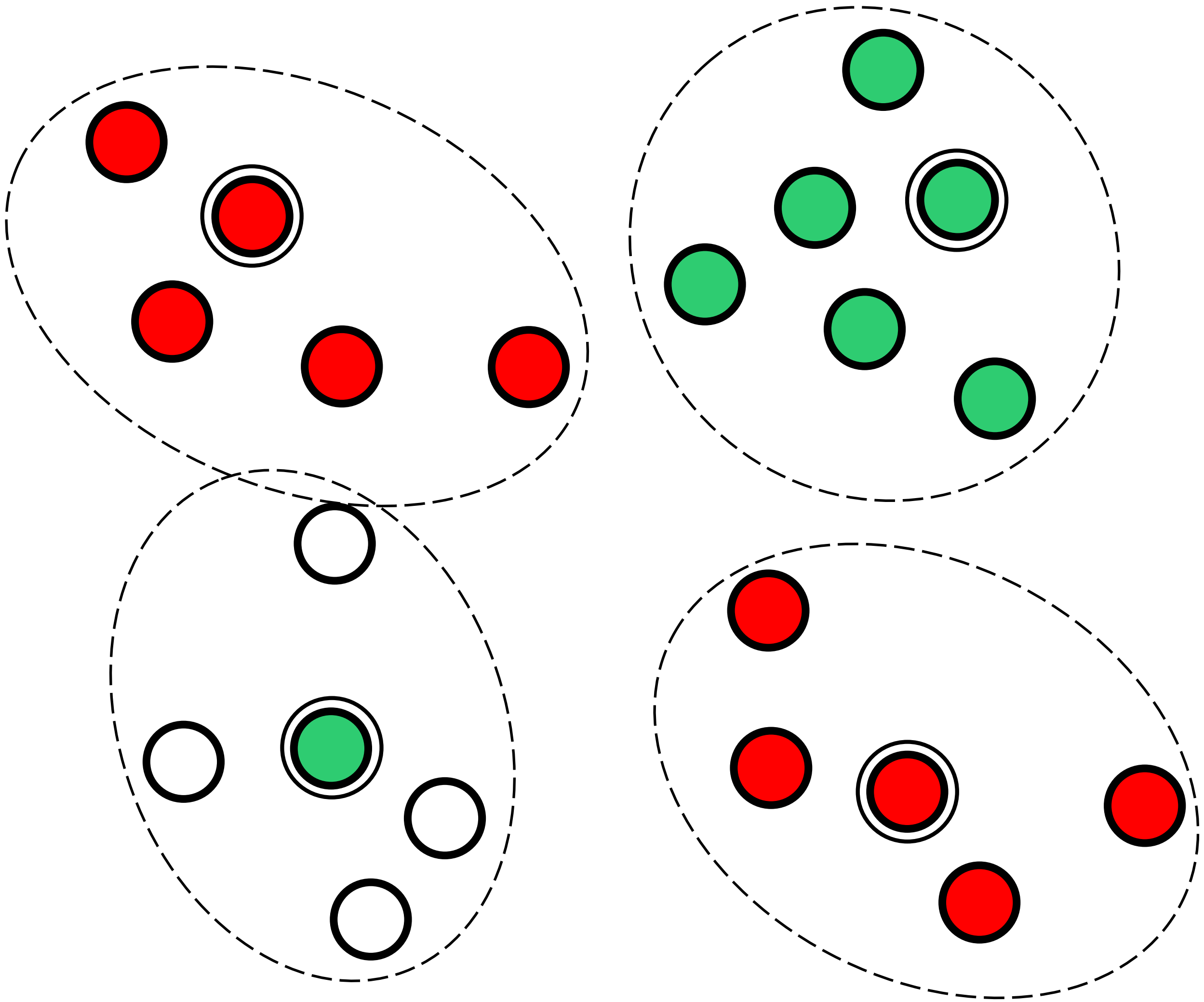

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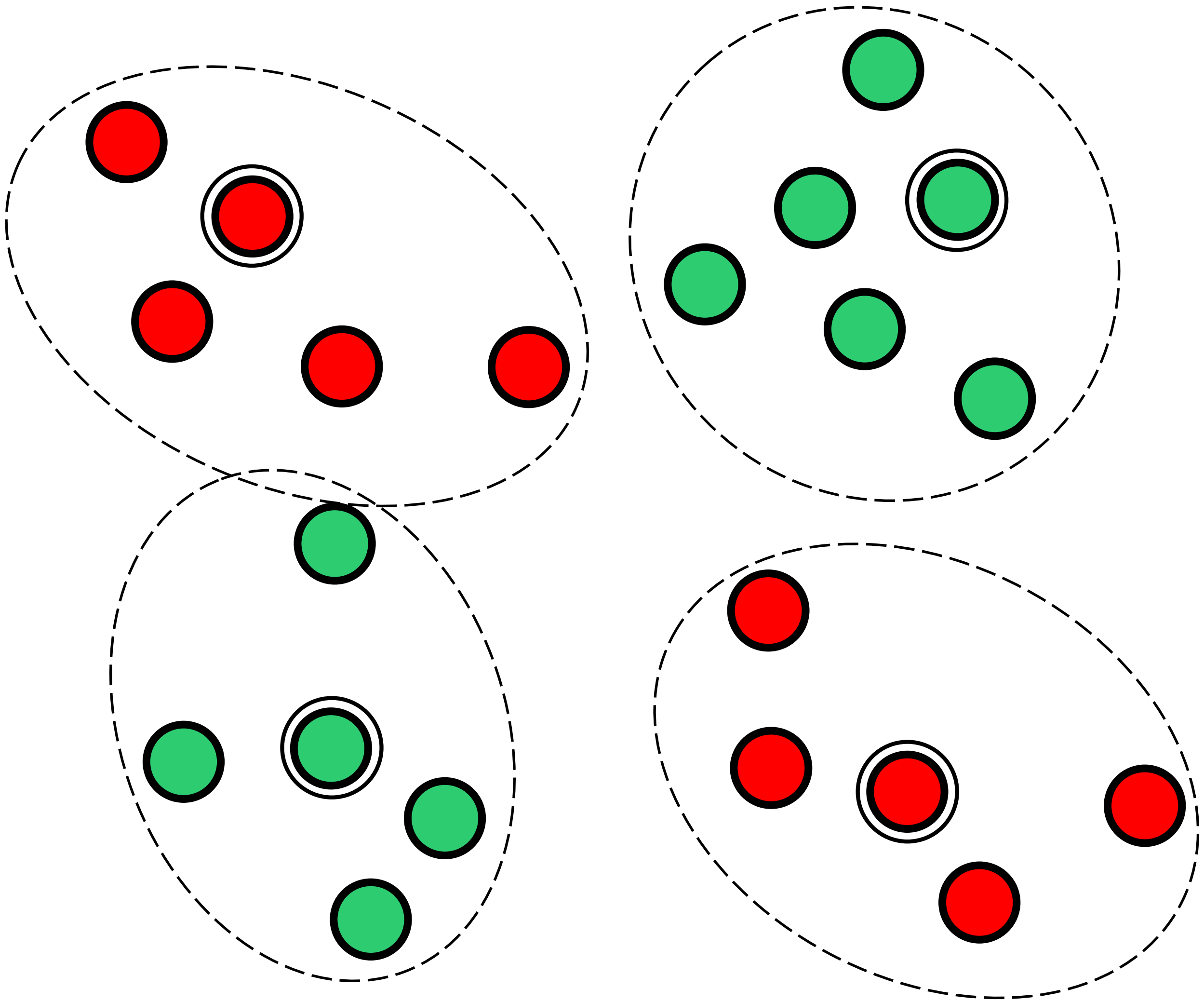

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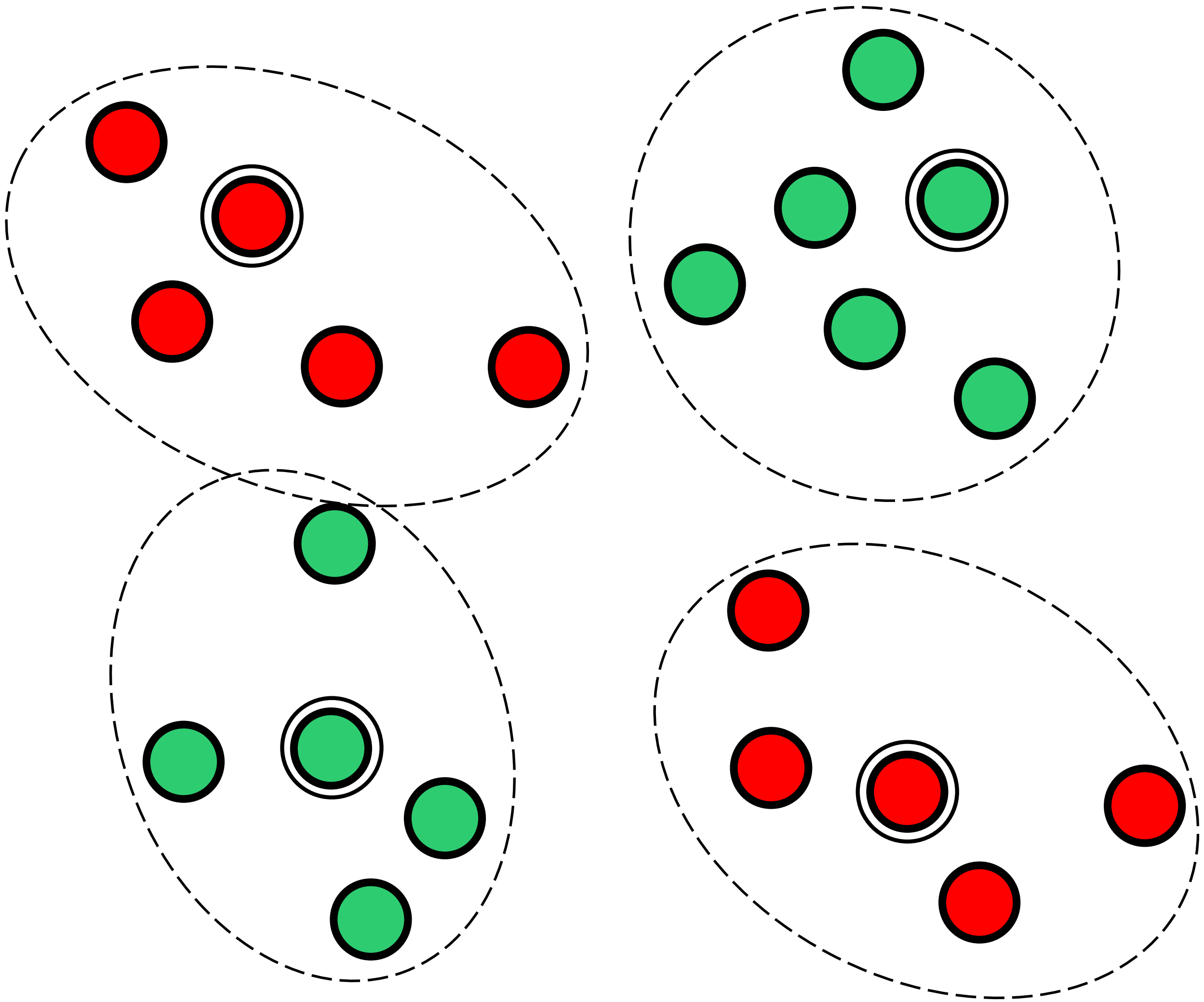

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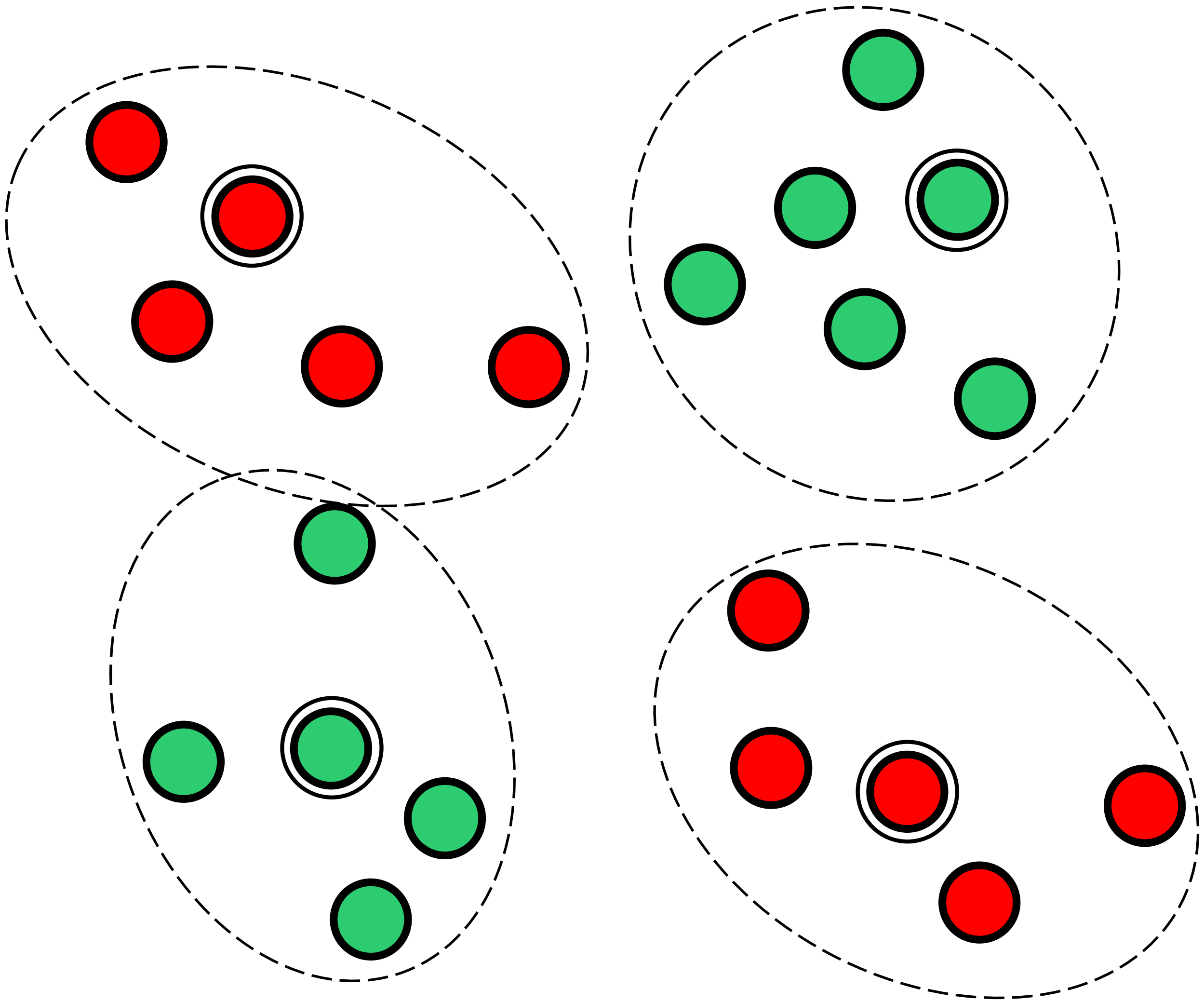

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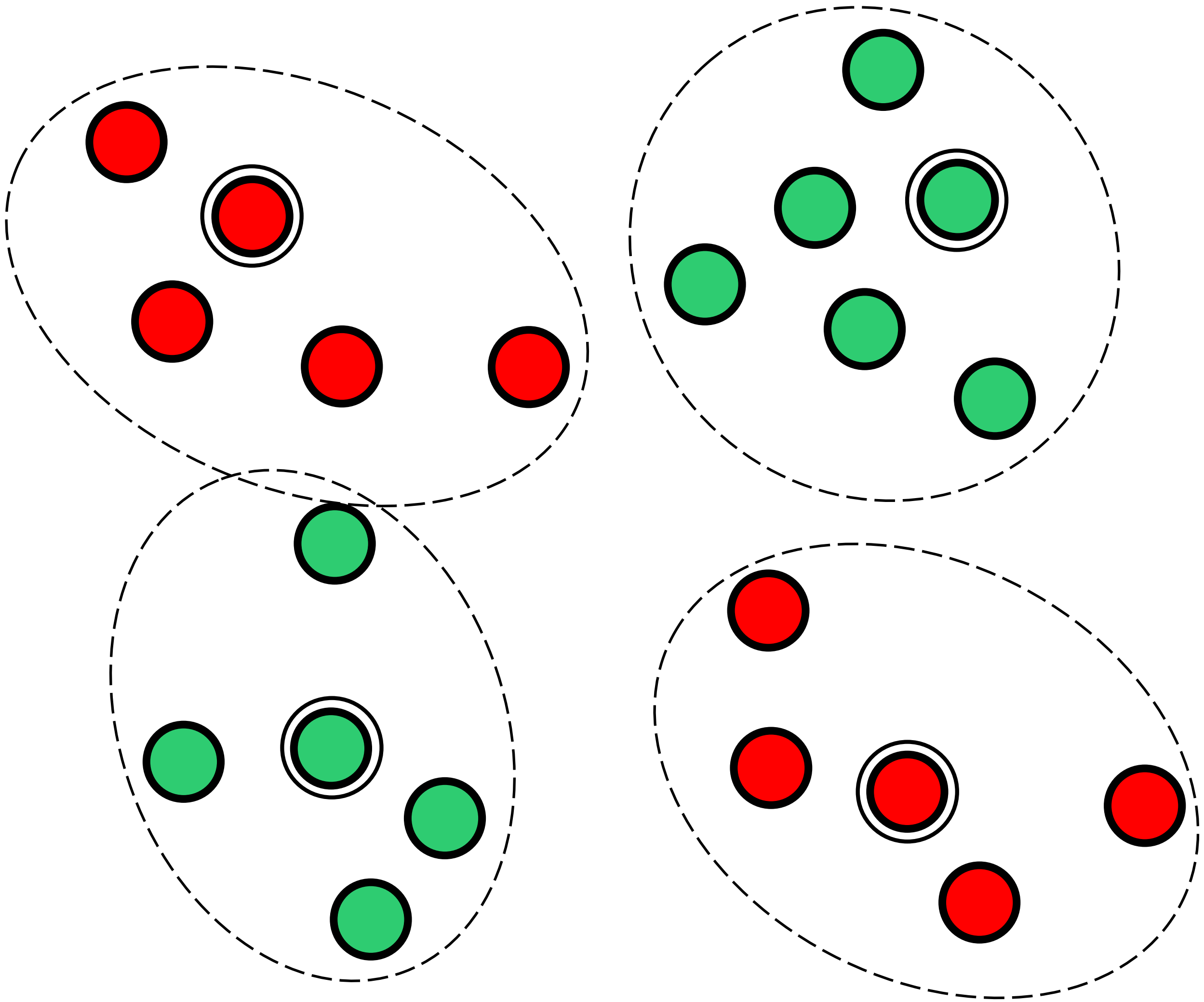

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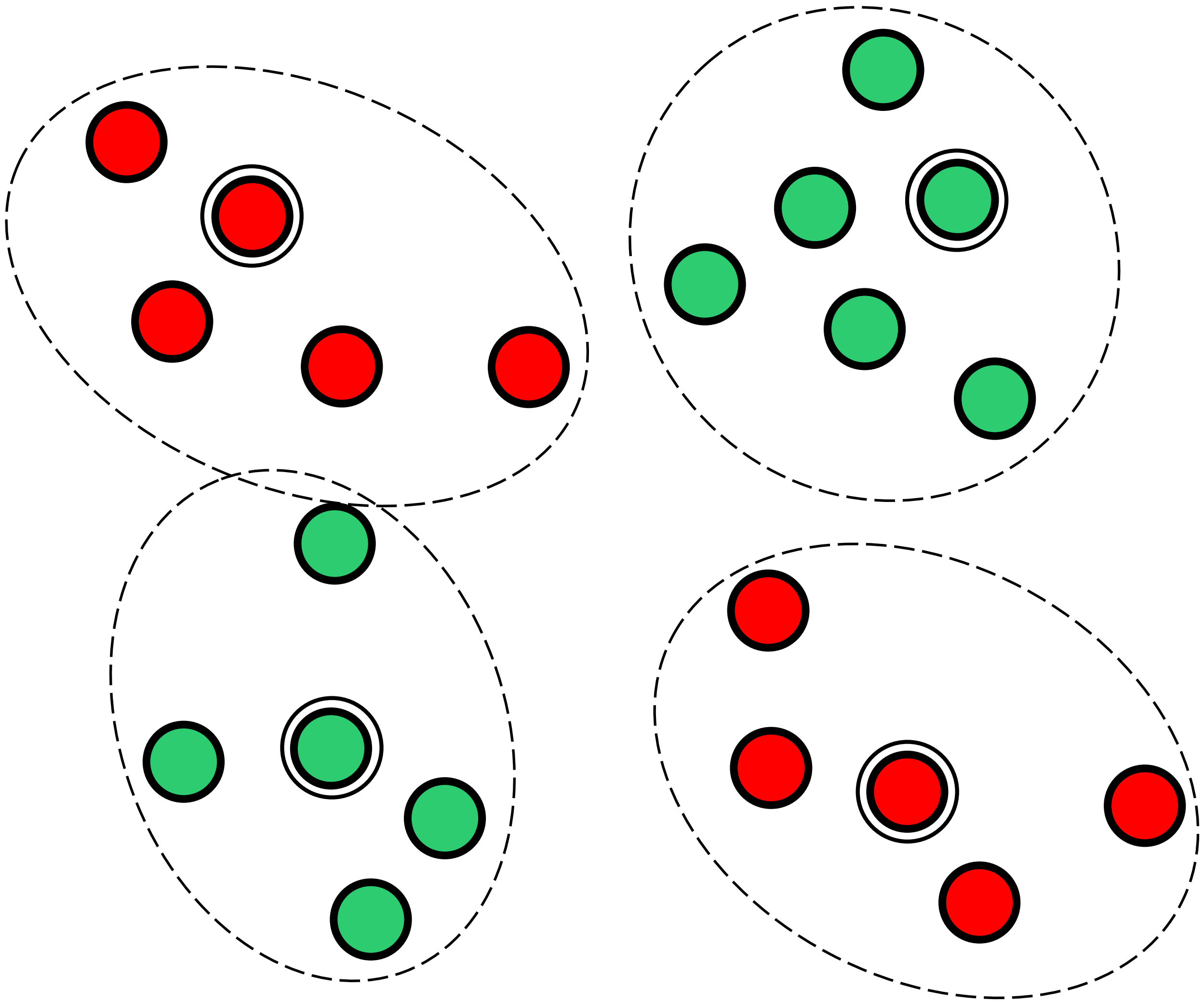

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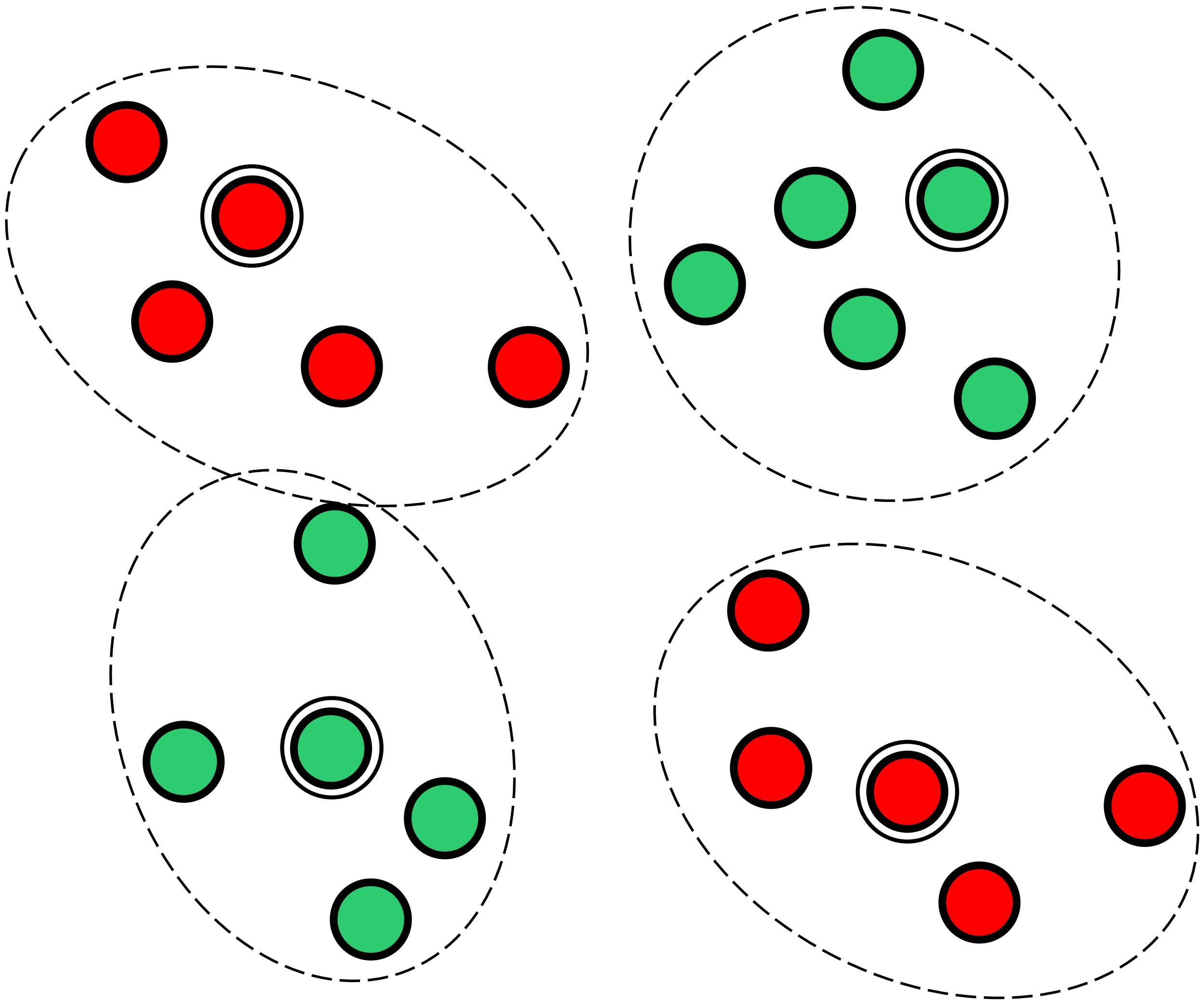

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  - Clustering mistakes disastrous
- Many solutions – discuss one

Active Learning Attempt I

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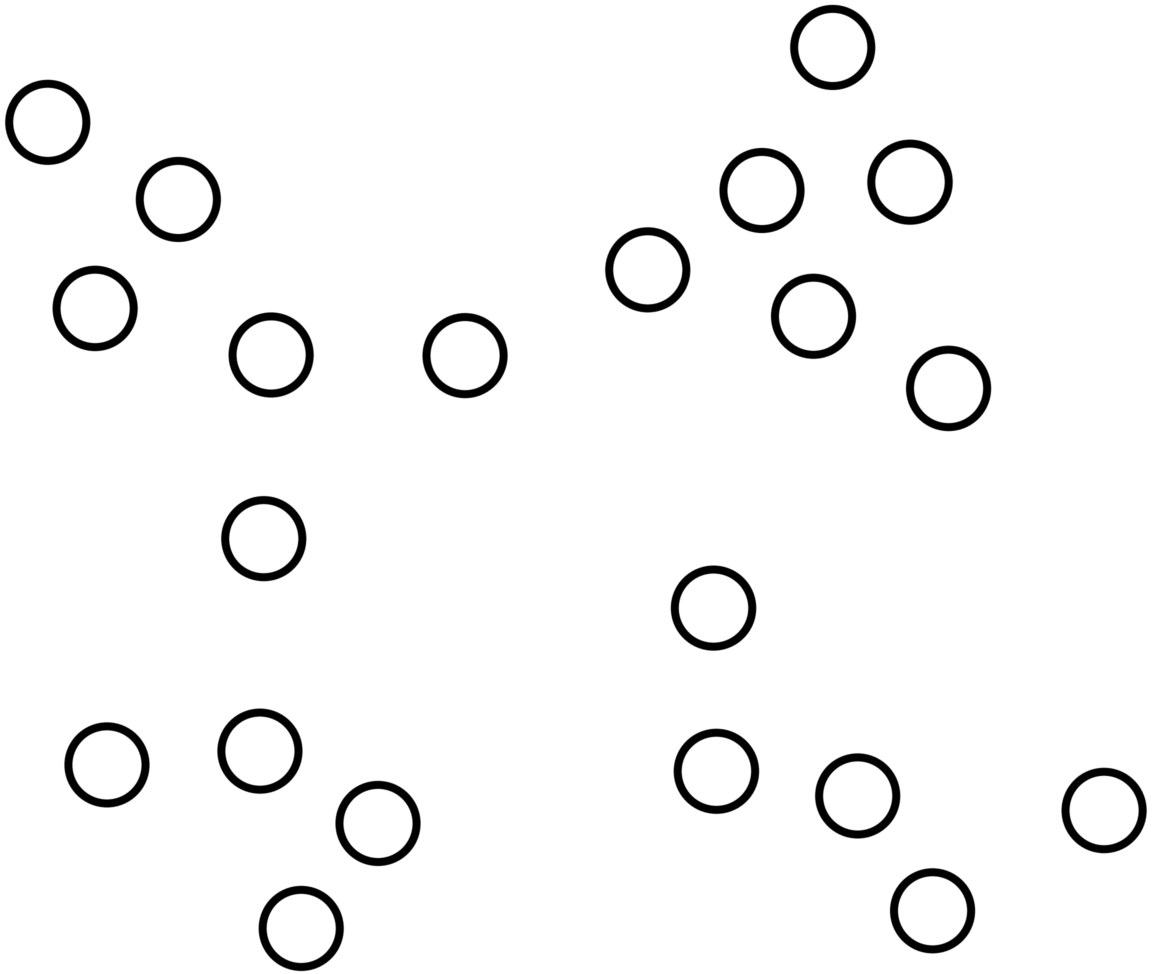

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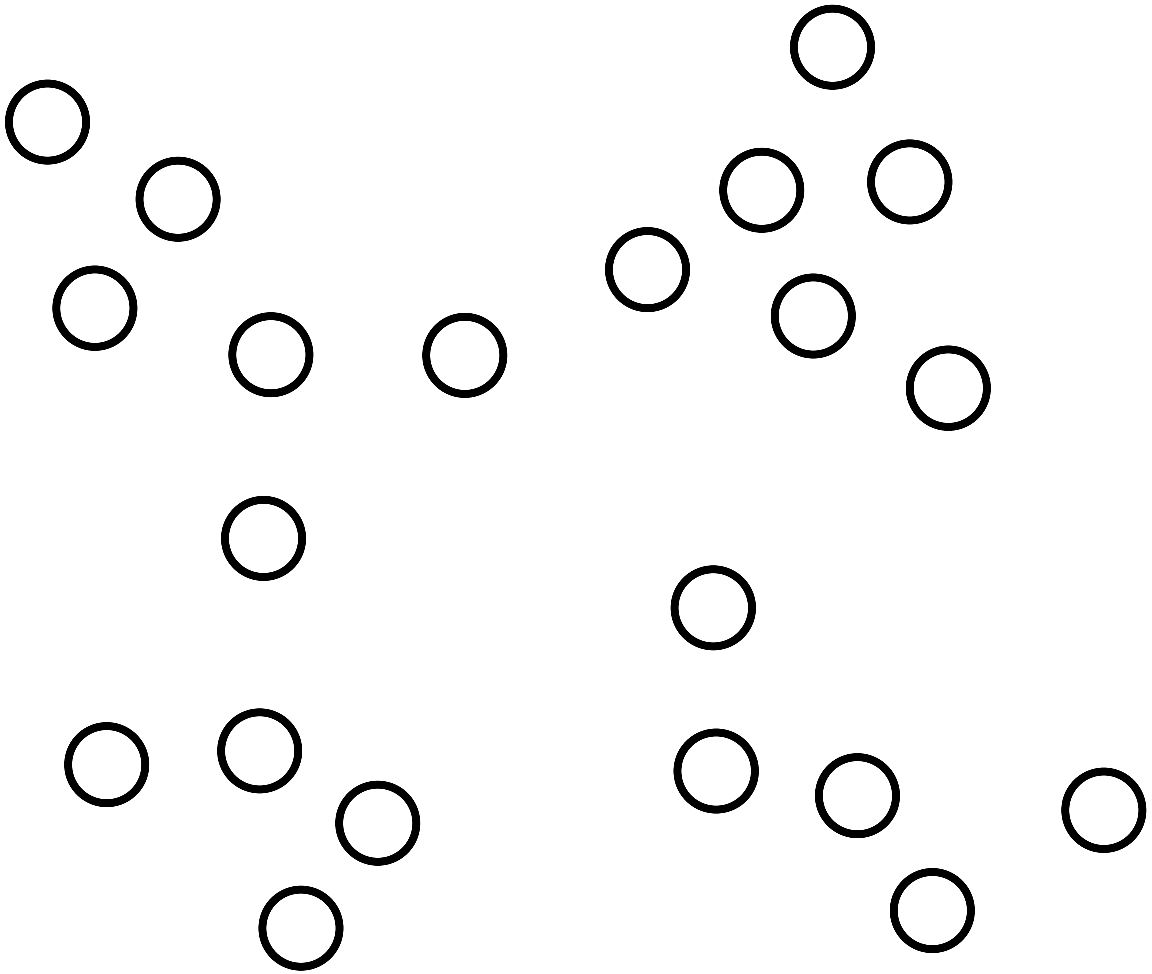

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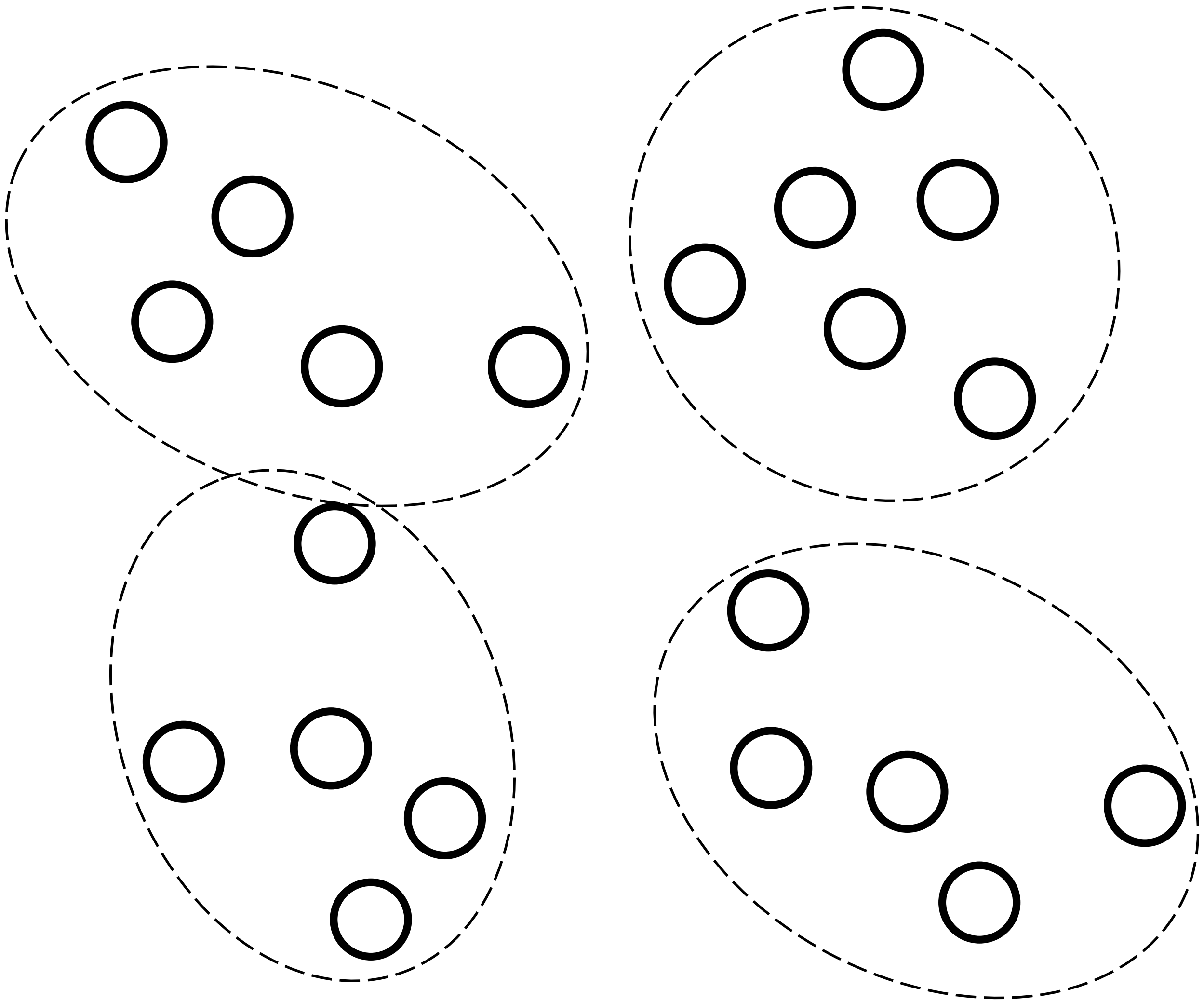

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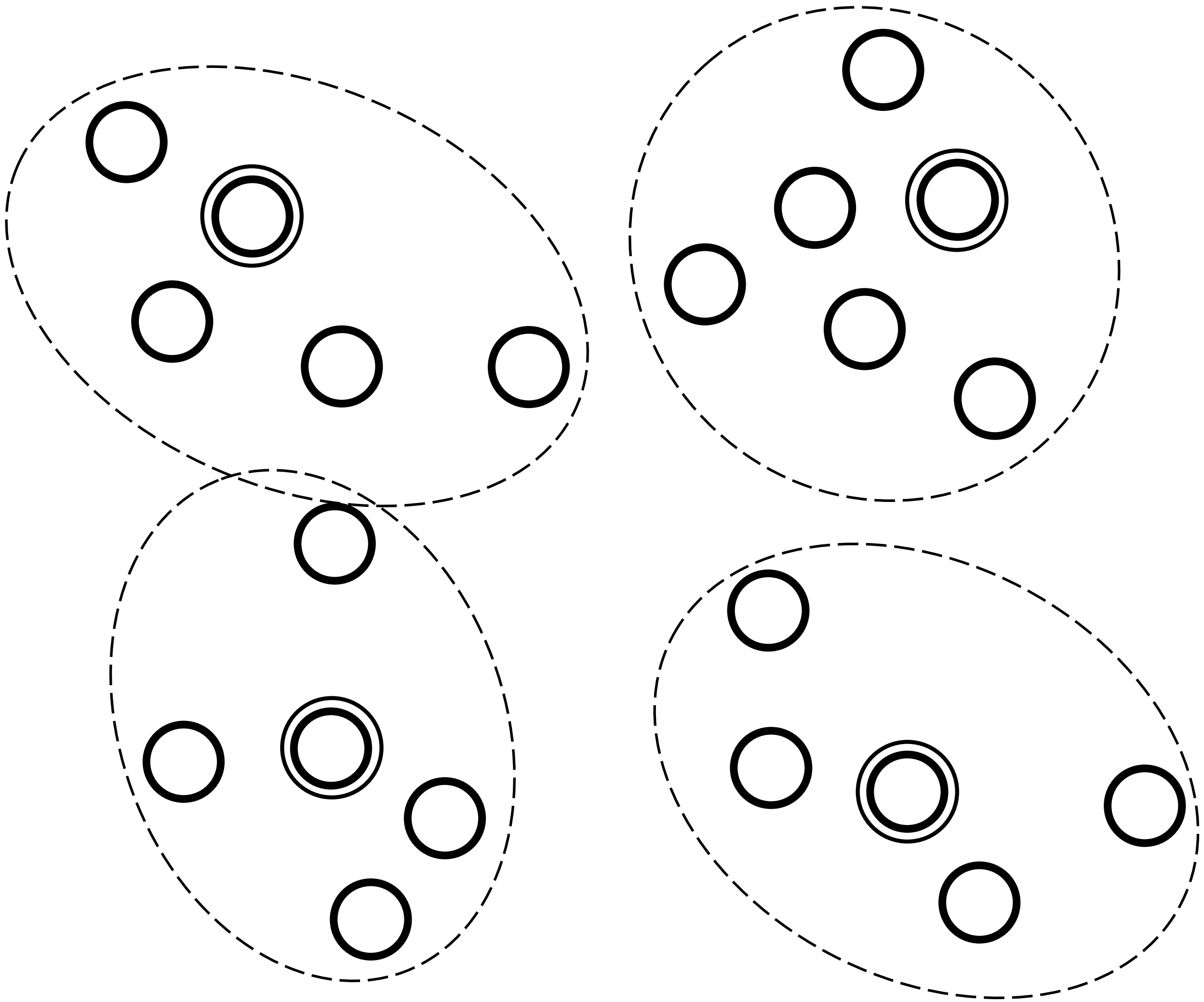

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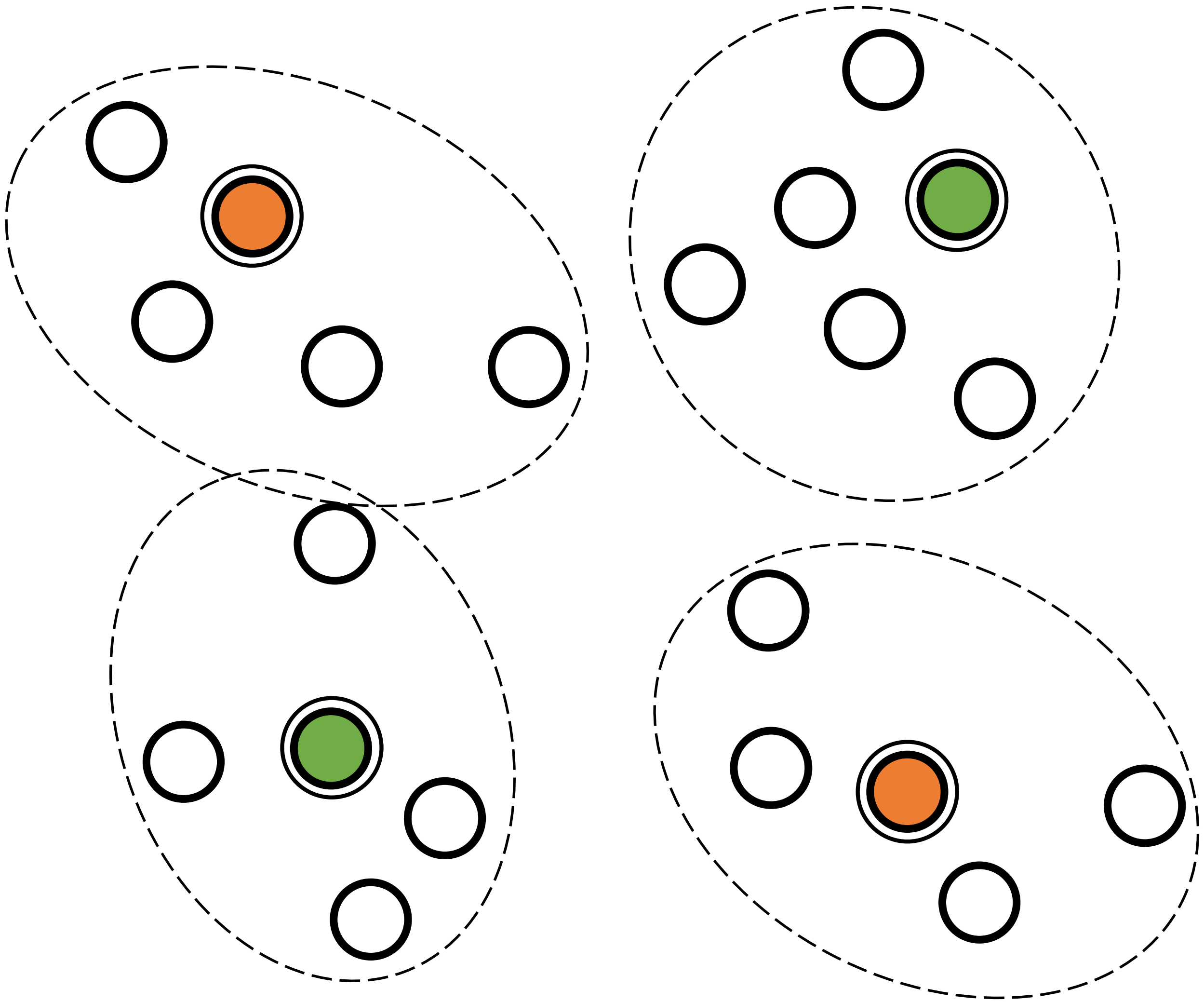

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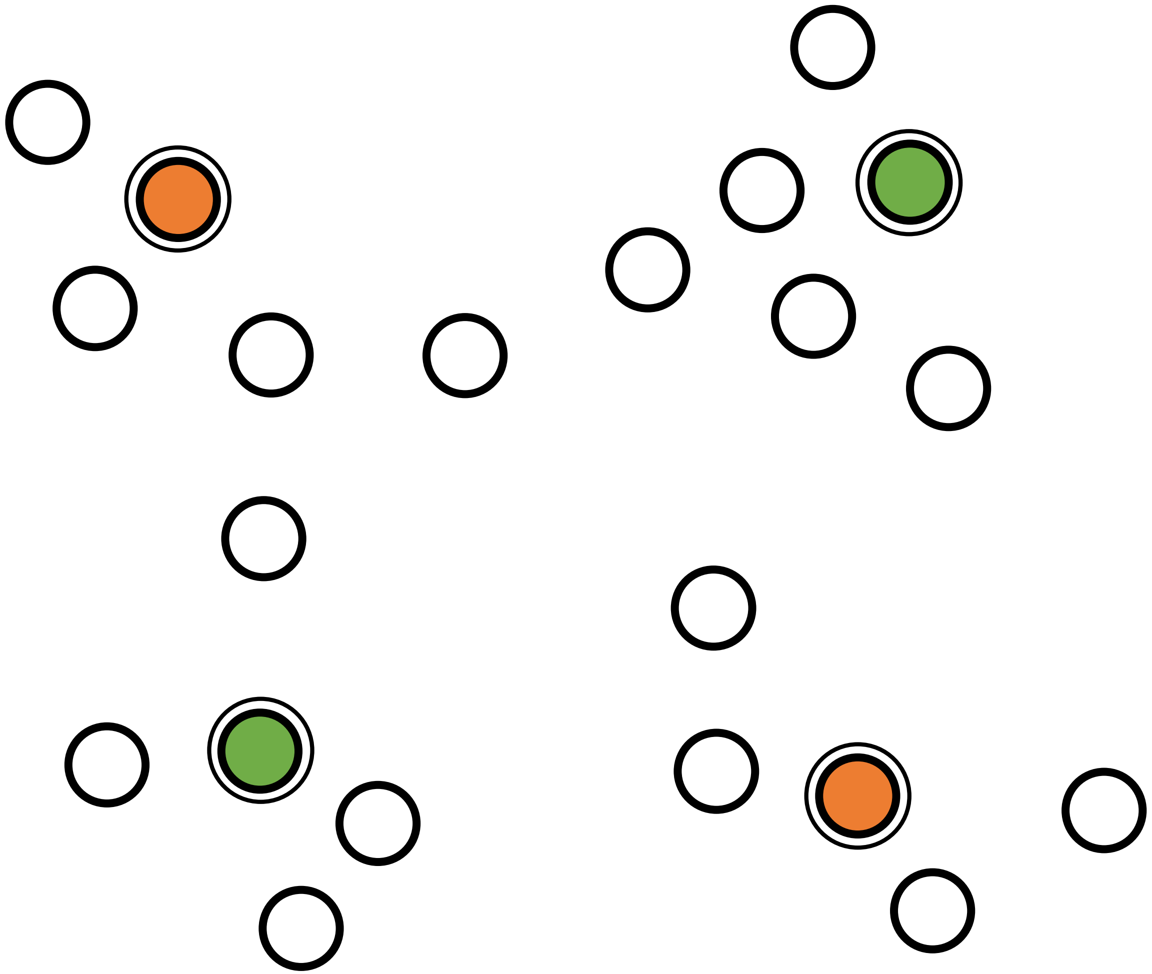

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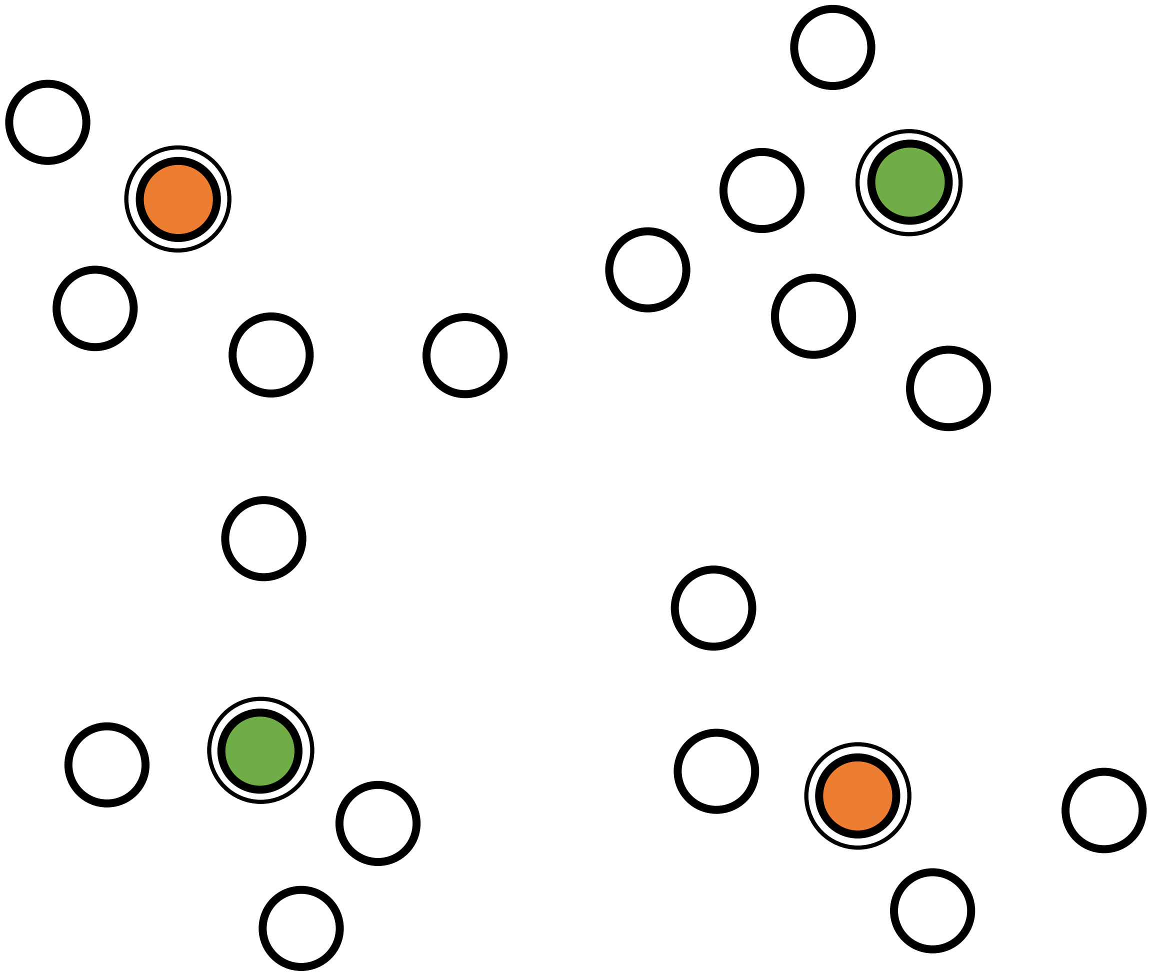

- Cluster and get labels for cluster representatives
- Create a "similarity graph" over data points

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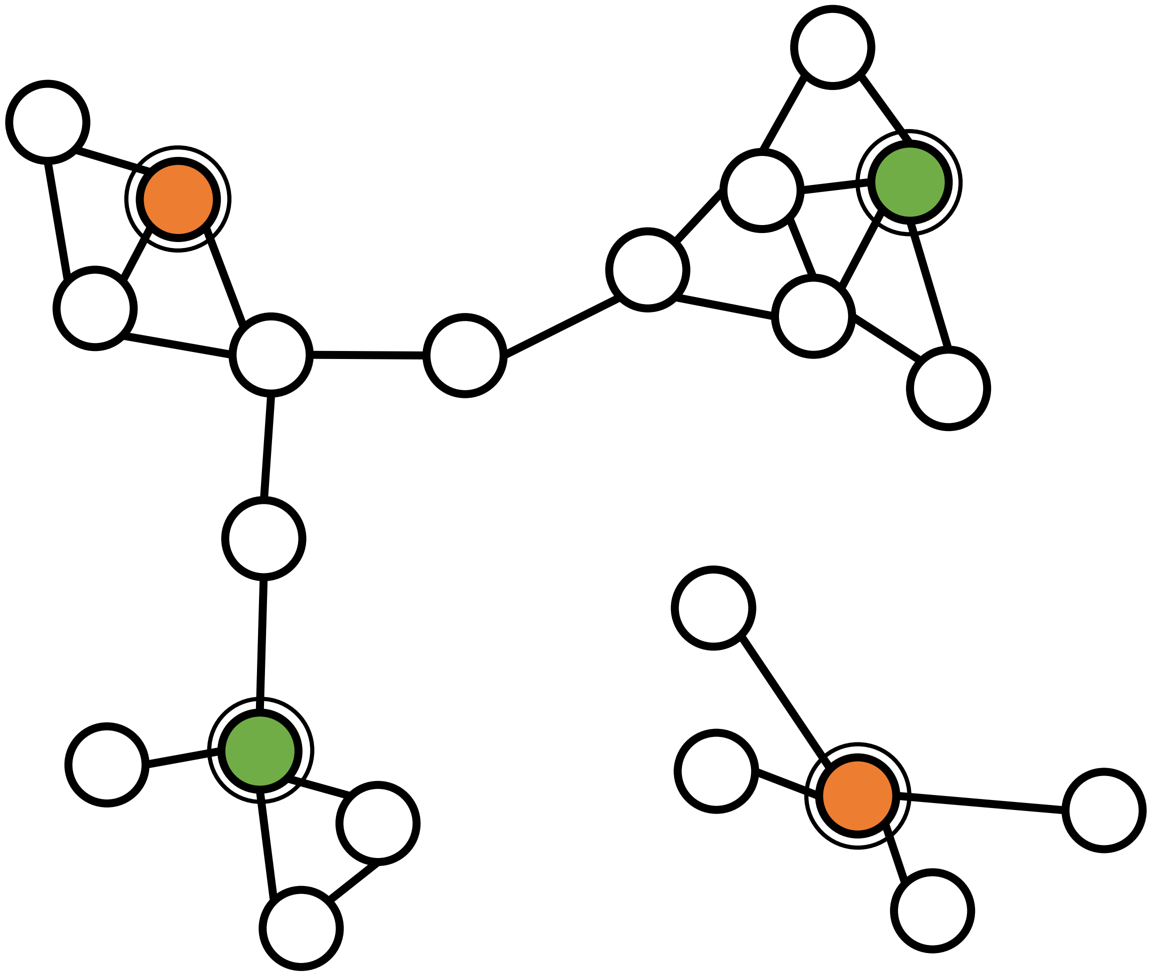

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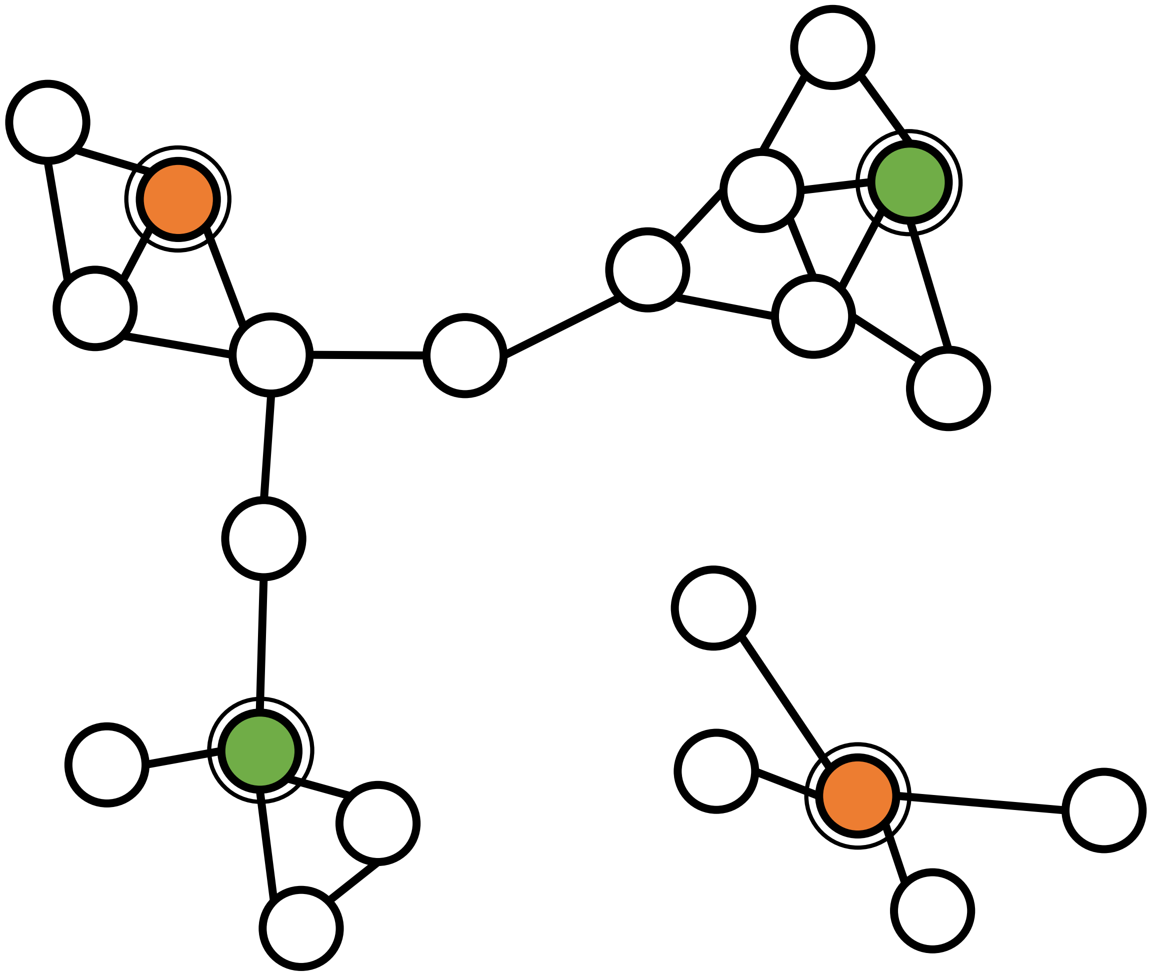

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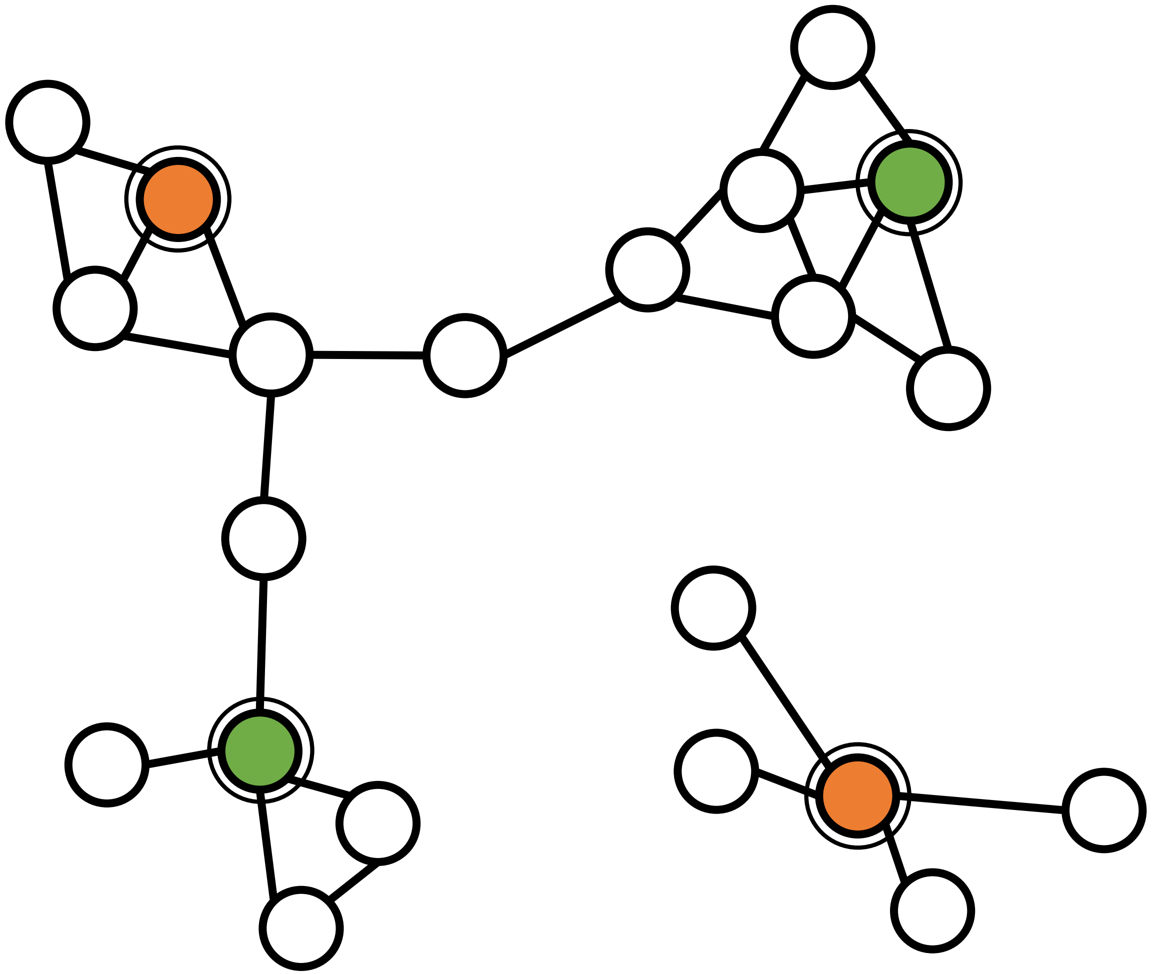

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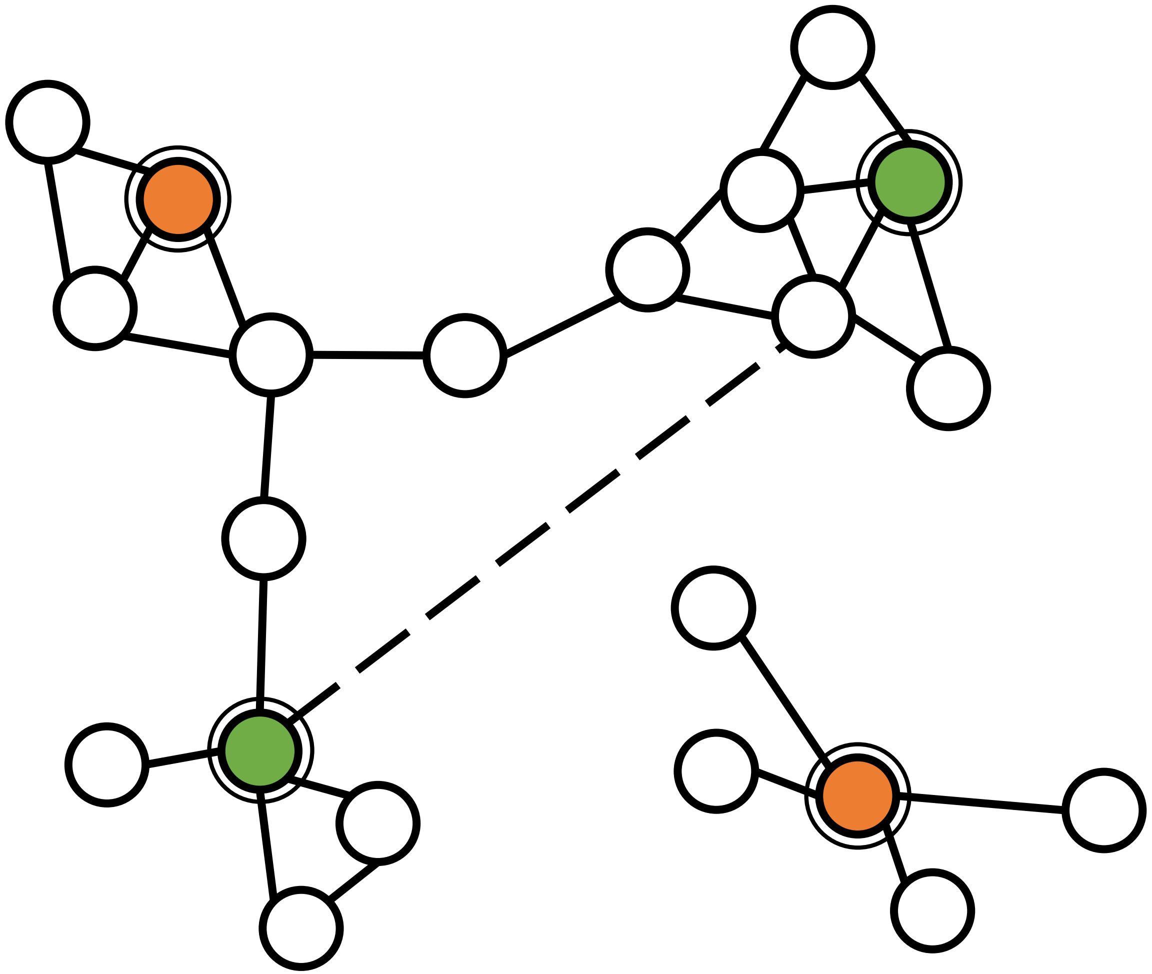

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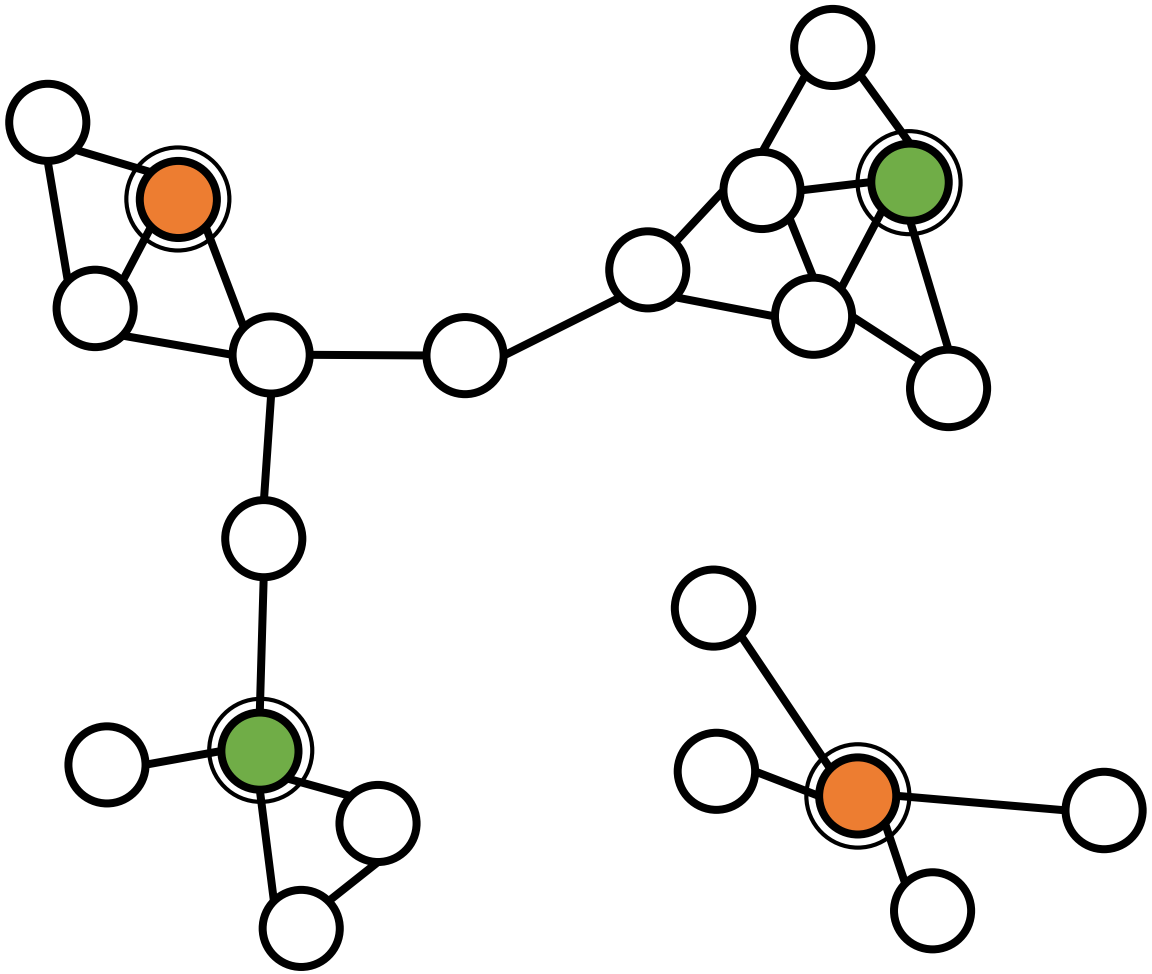

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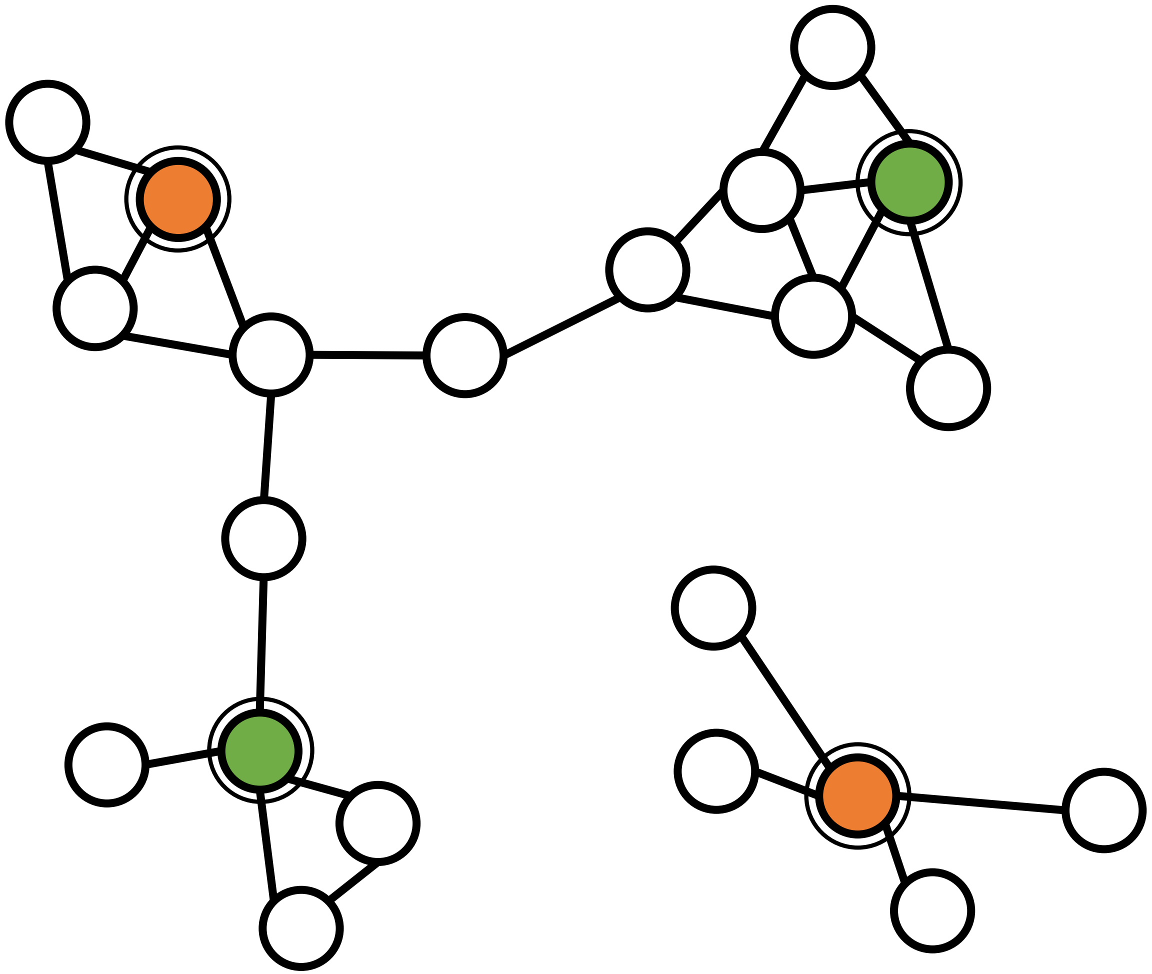

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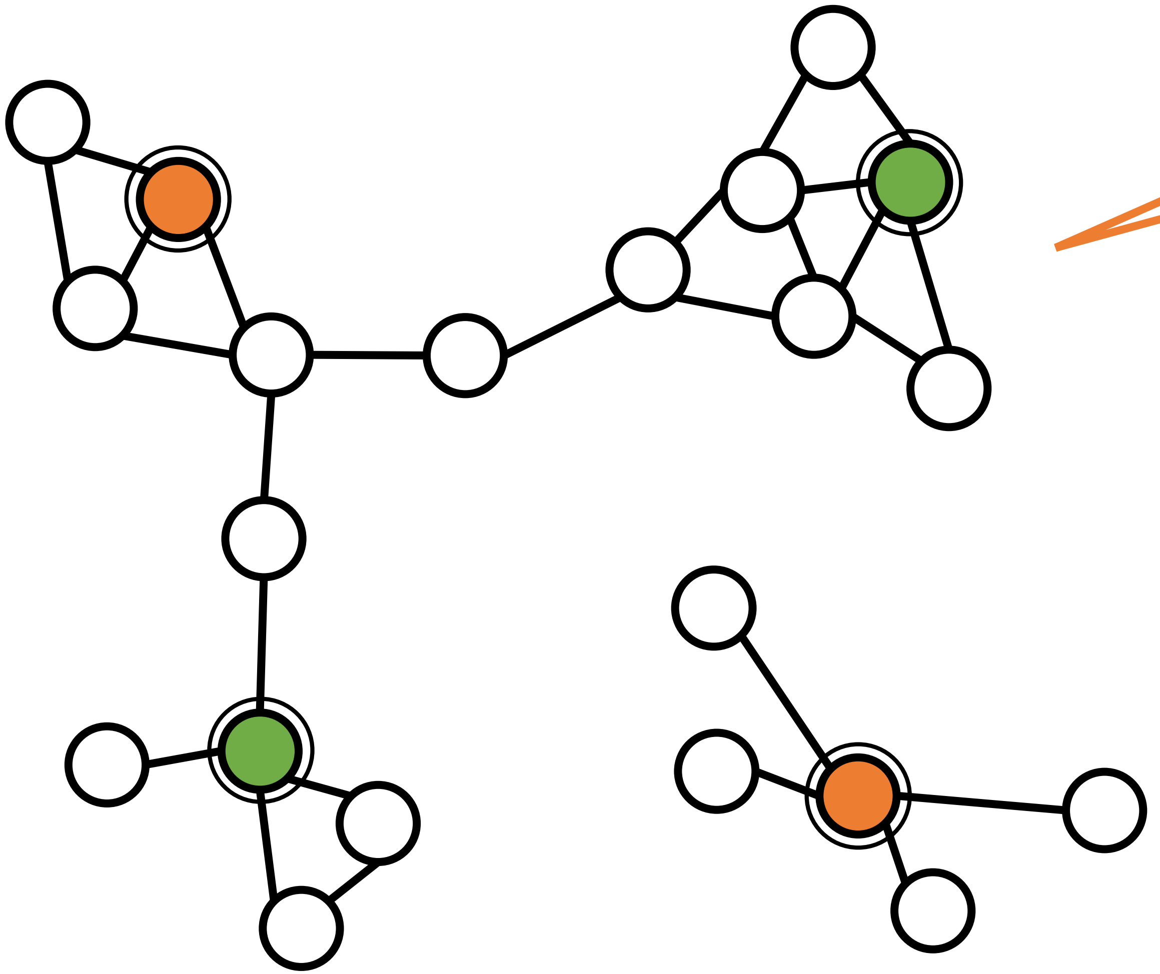

Many possibilities e.g. each node passes its label ± 1 to its neighbours multiplied by weight of the edge

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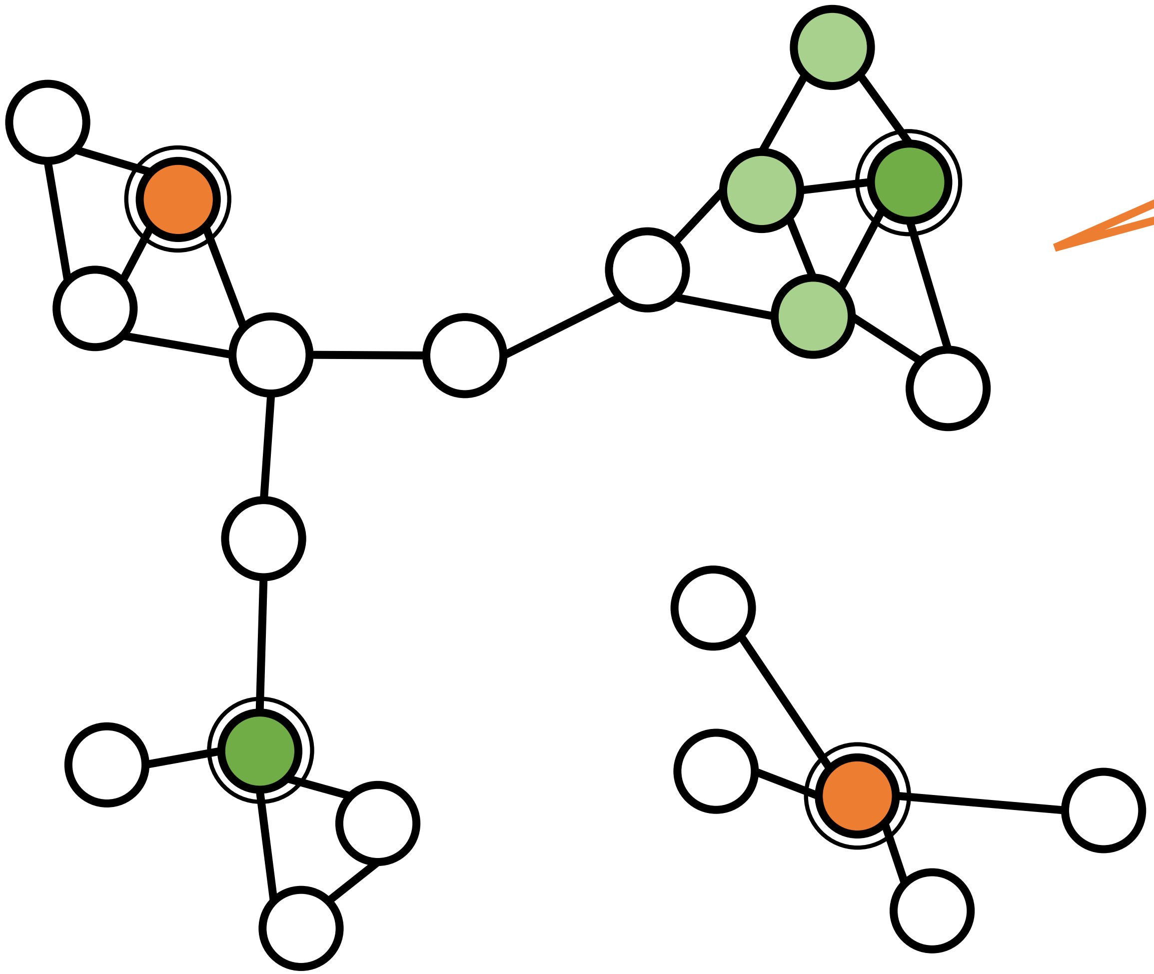

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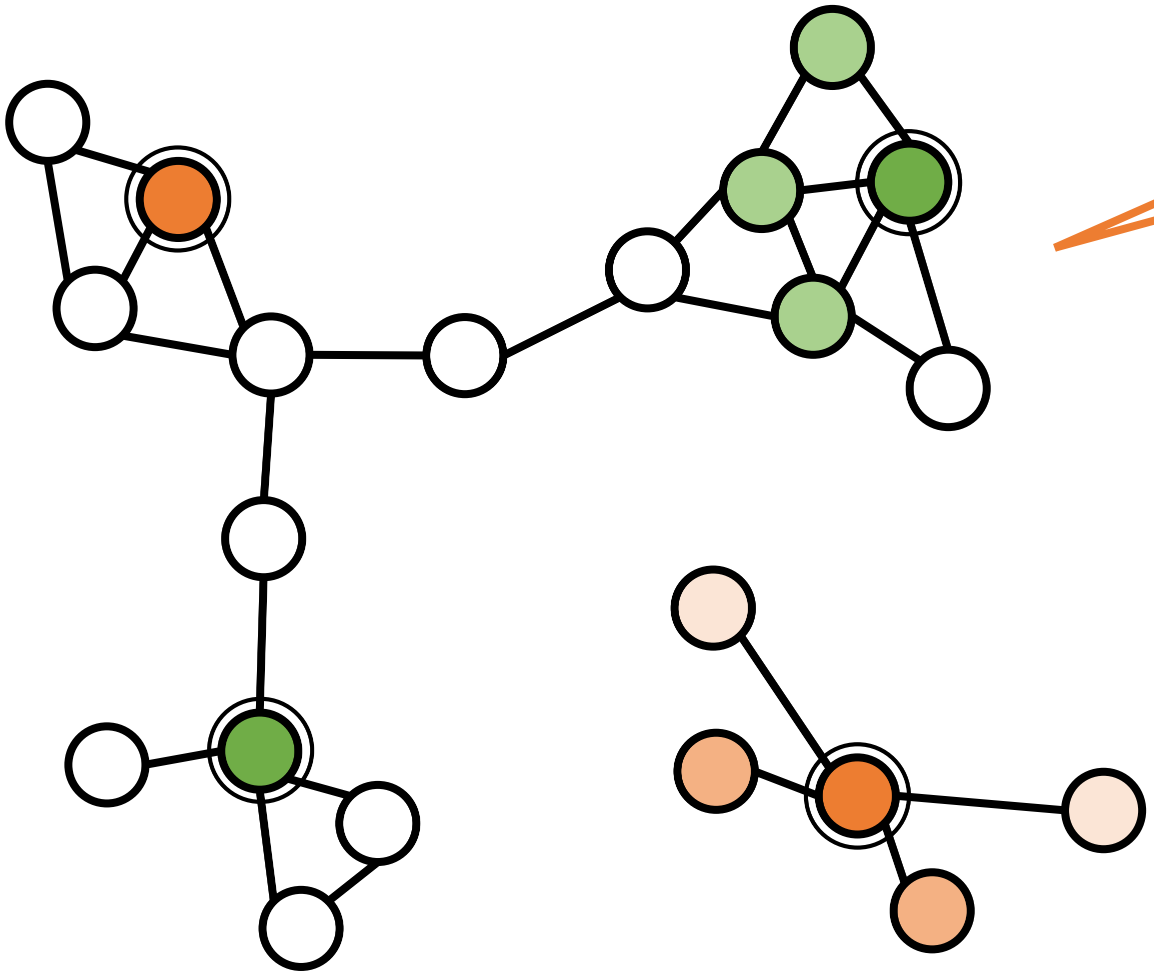

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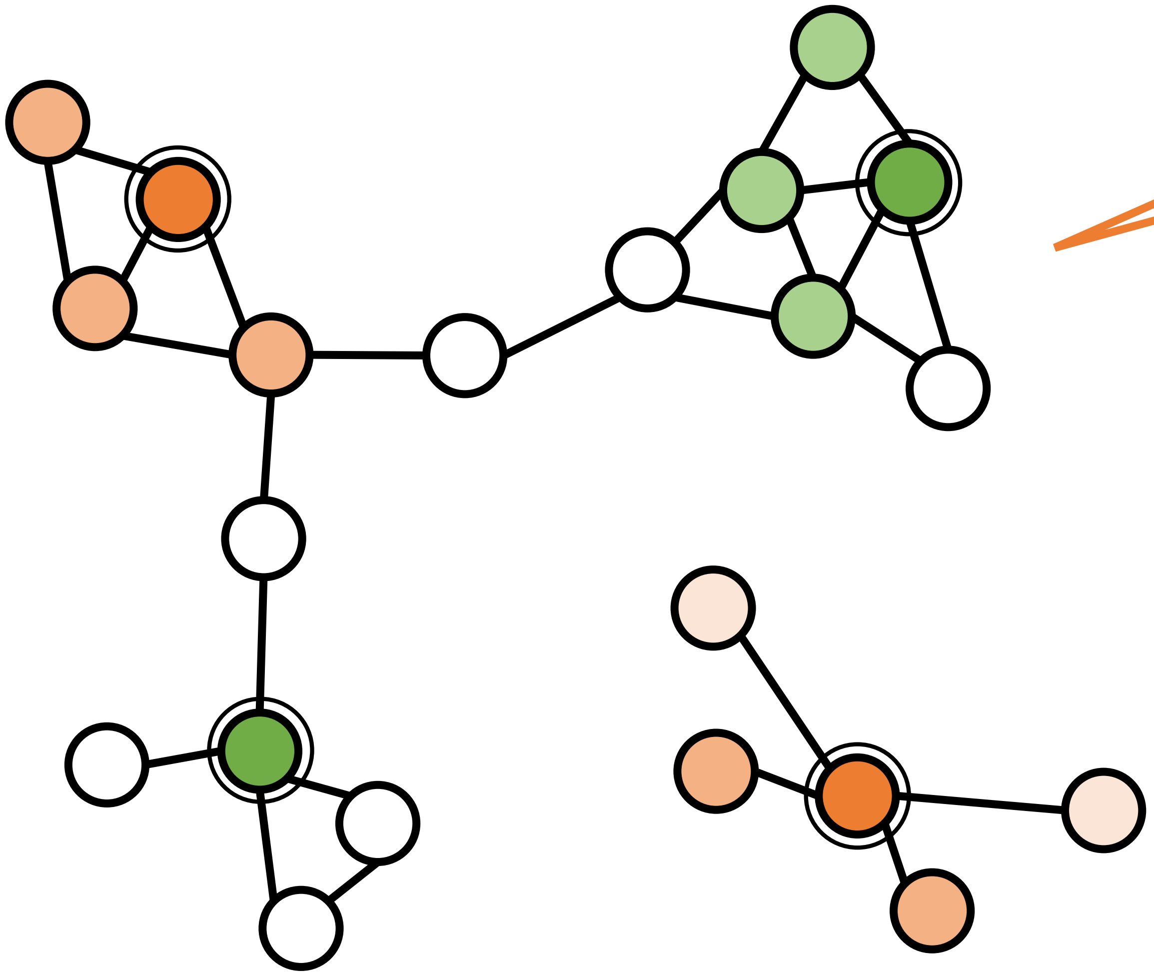

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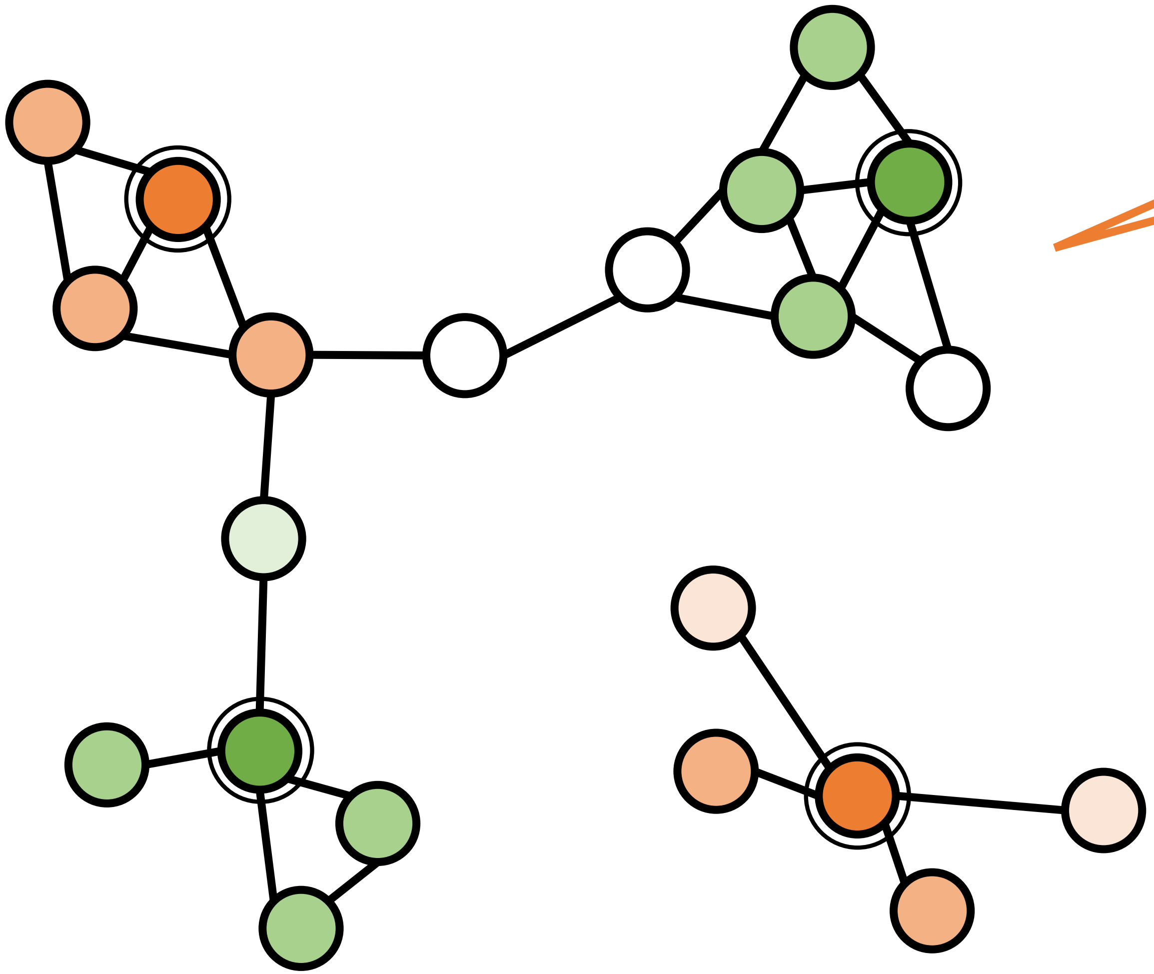

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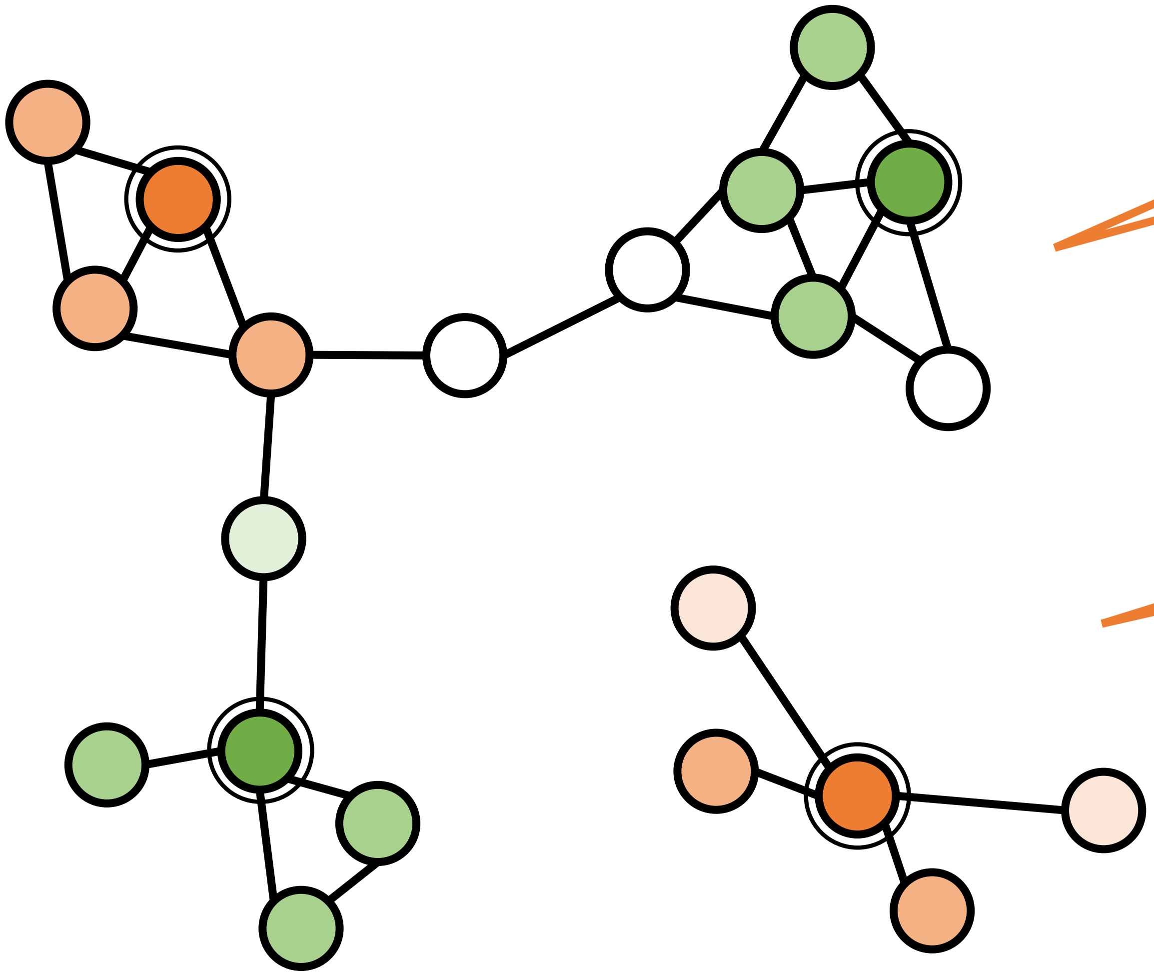

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Neighbors pass them on in successive iterations – "message passing"

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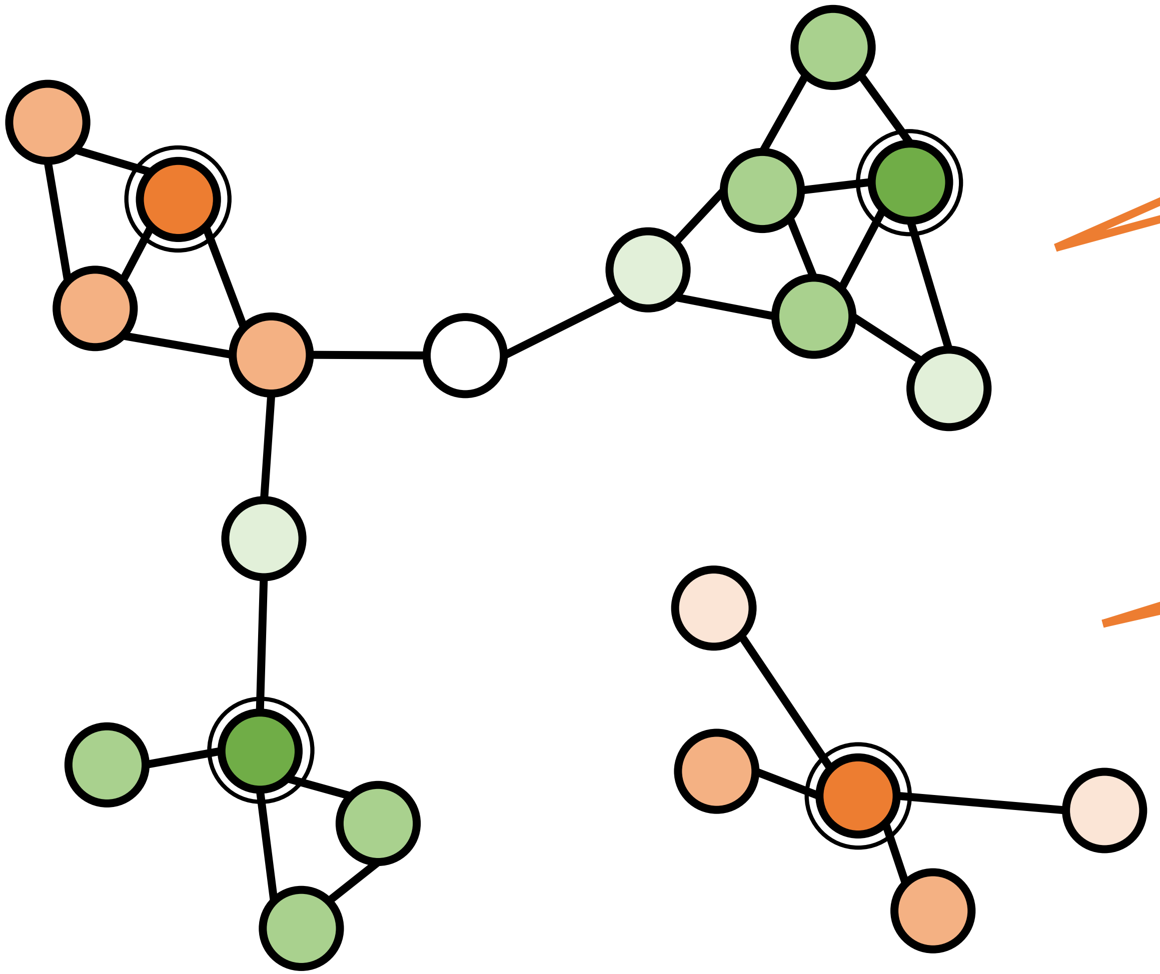

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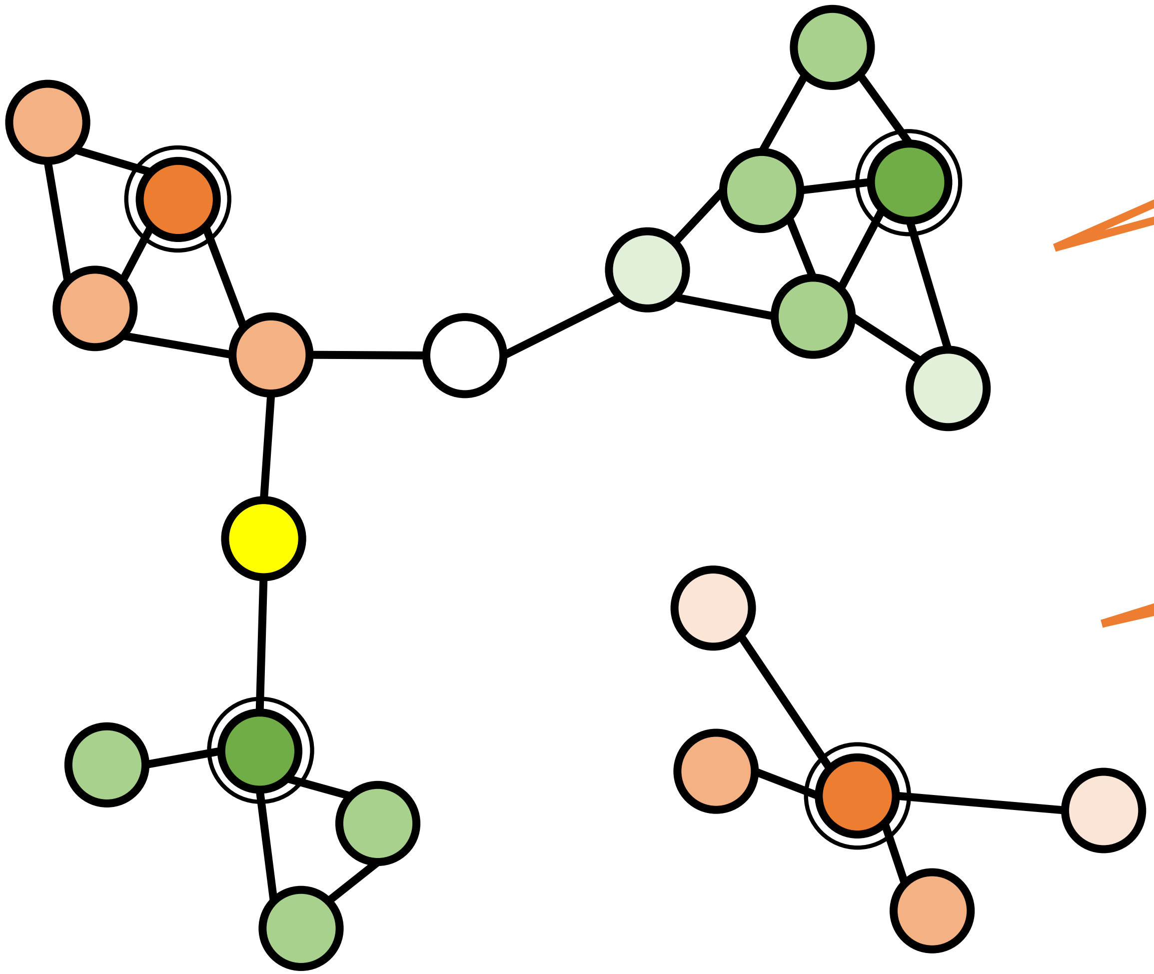

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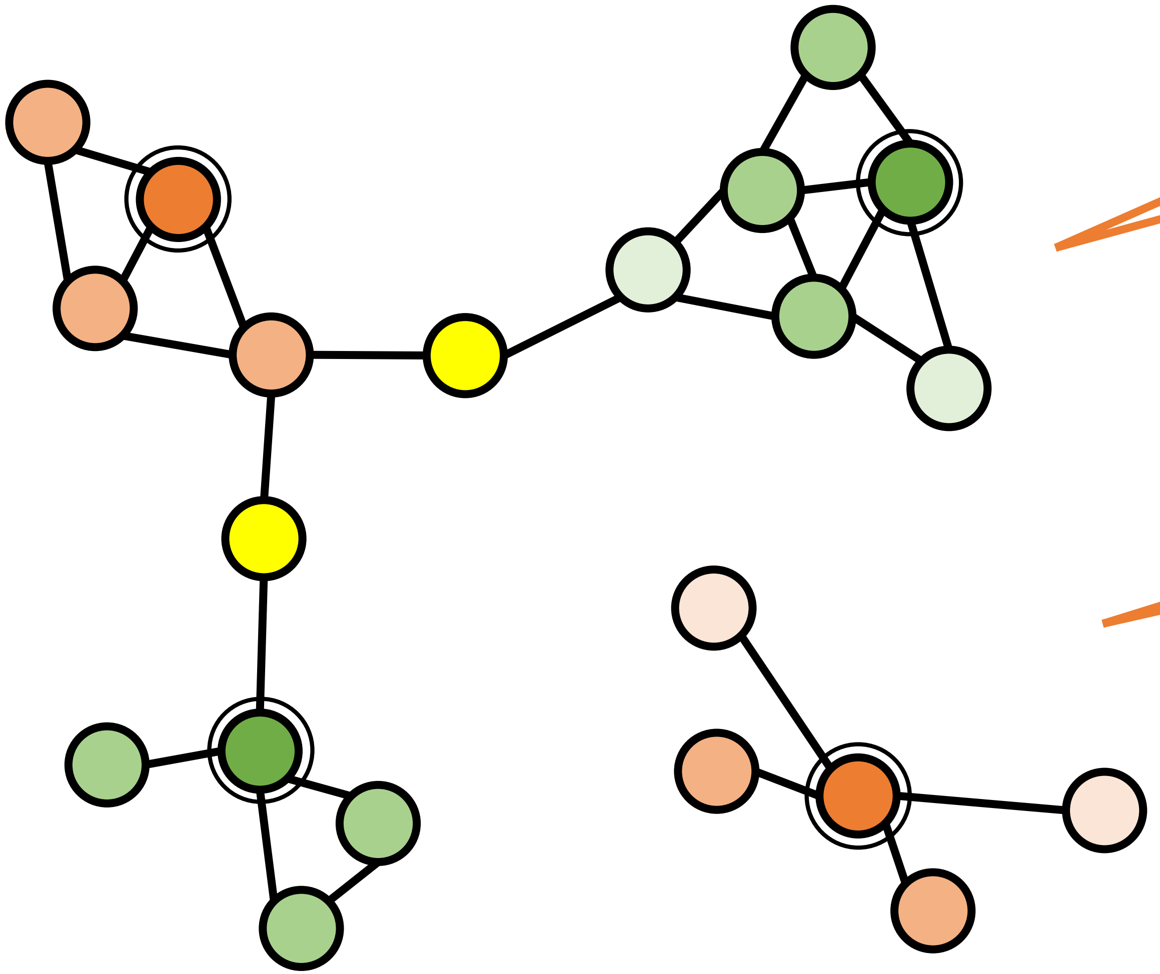

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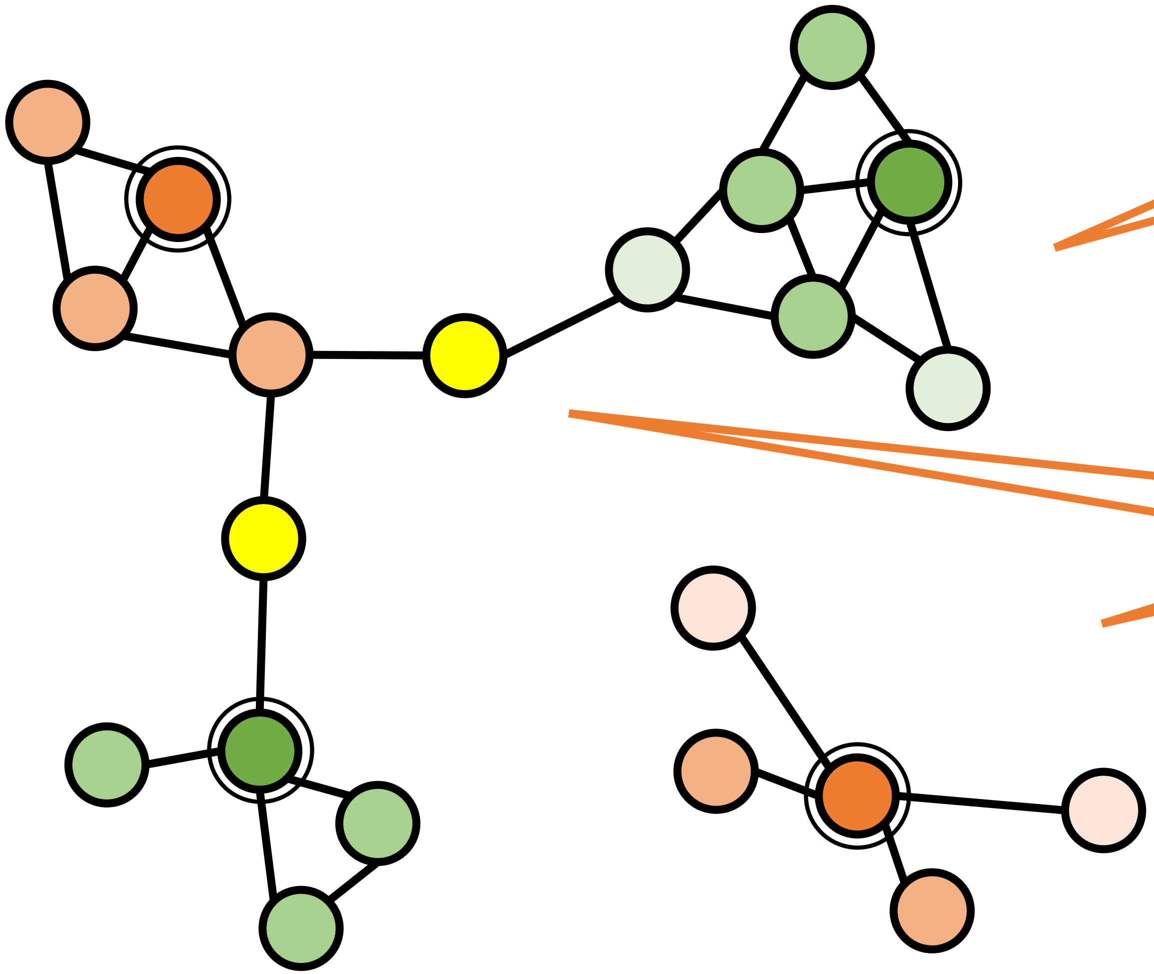

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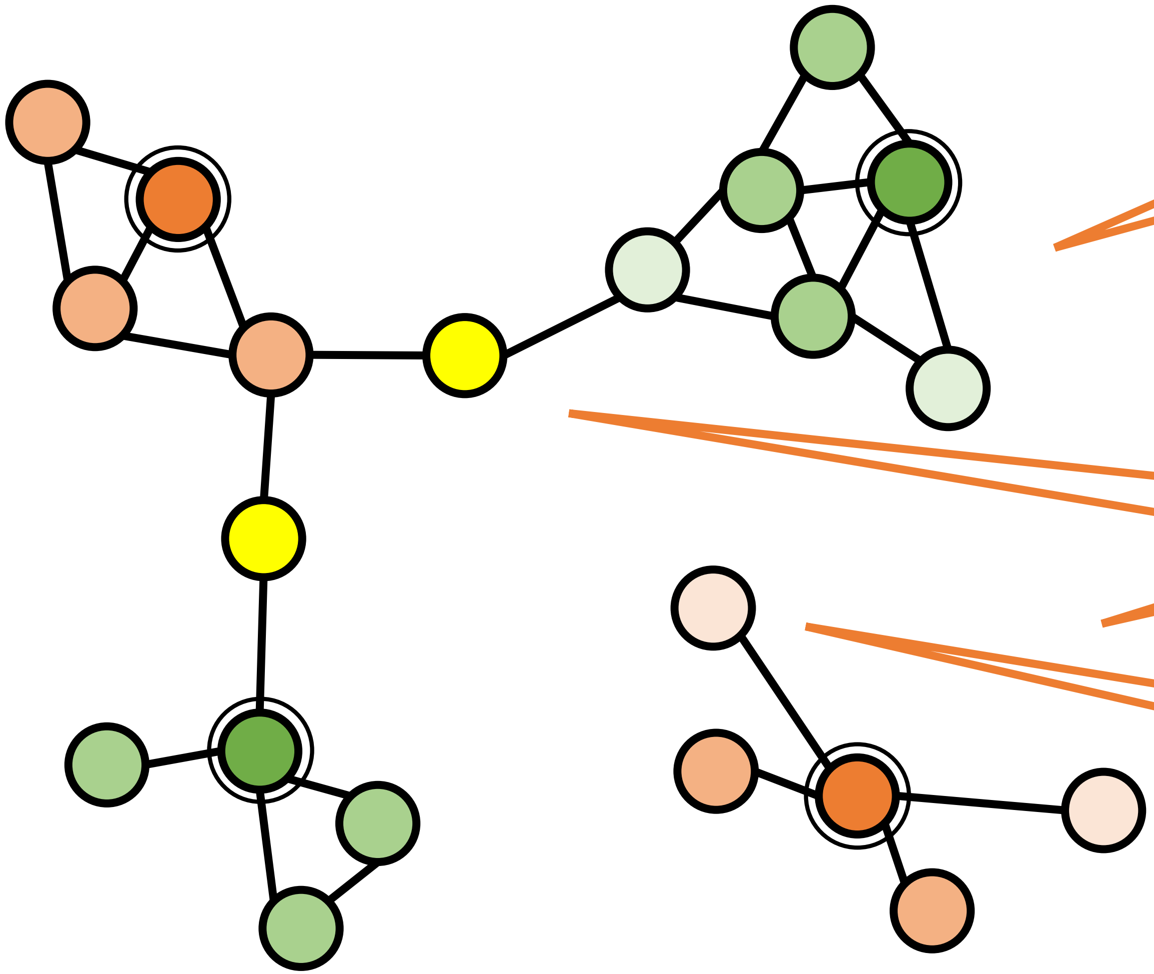

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… or be very unsure of their label

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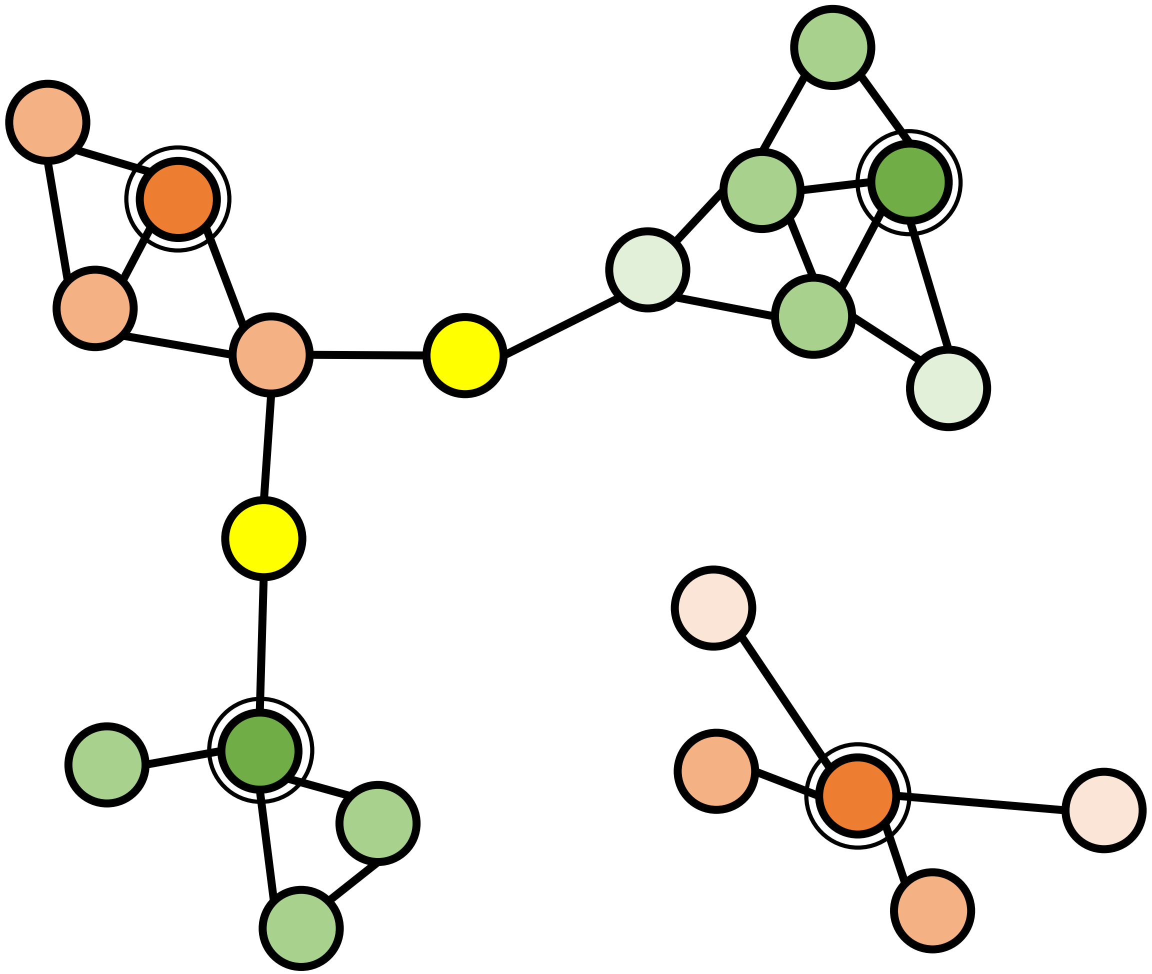

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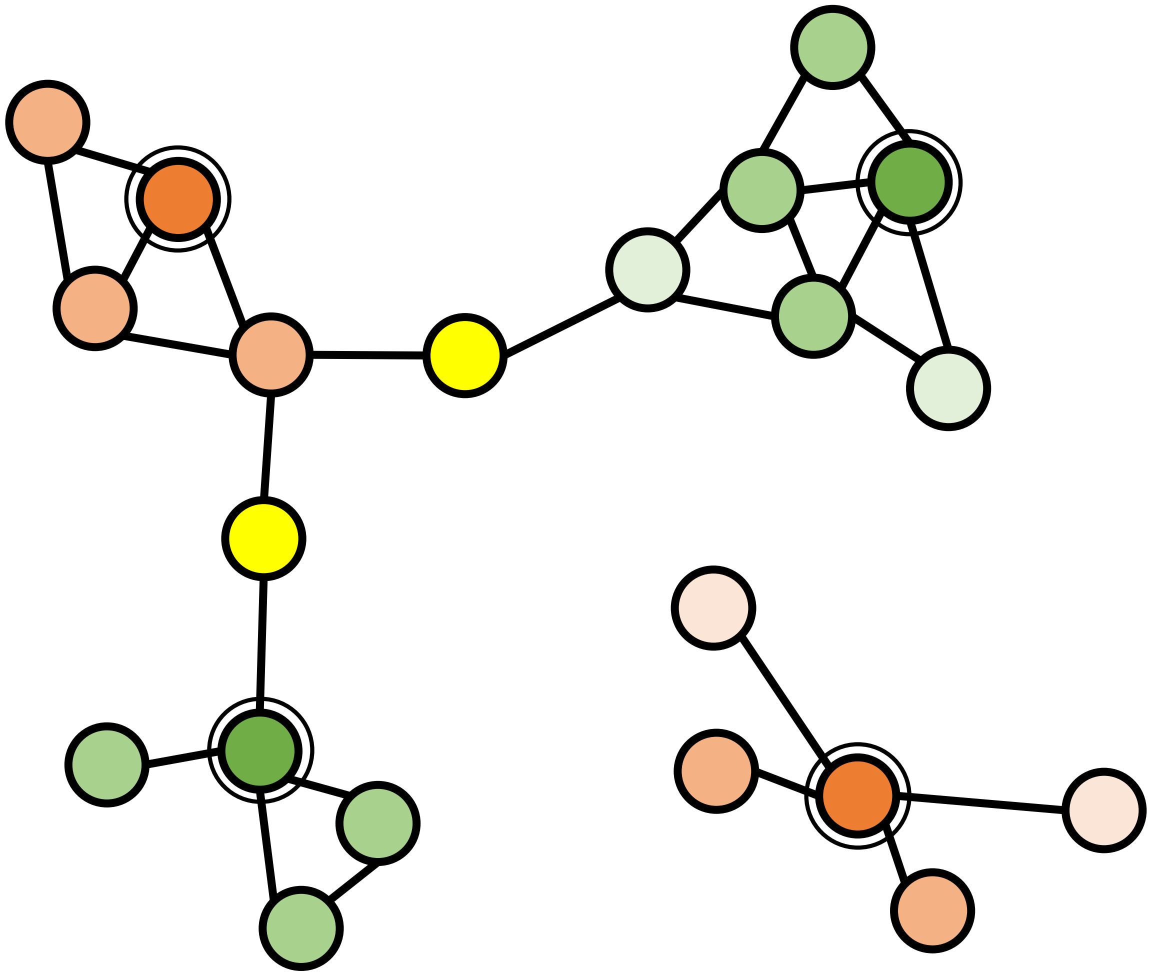

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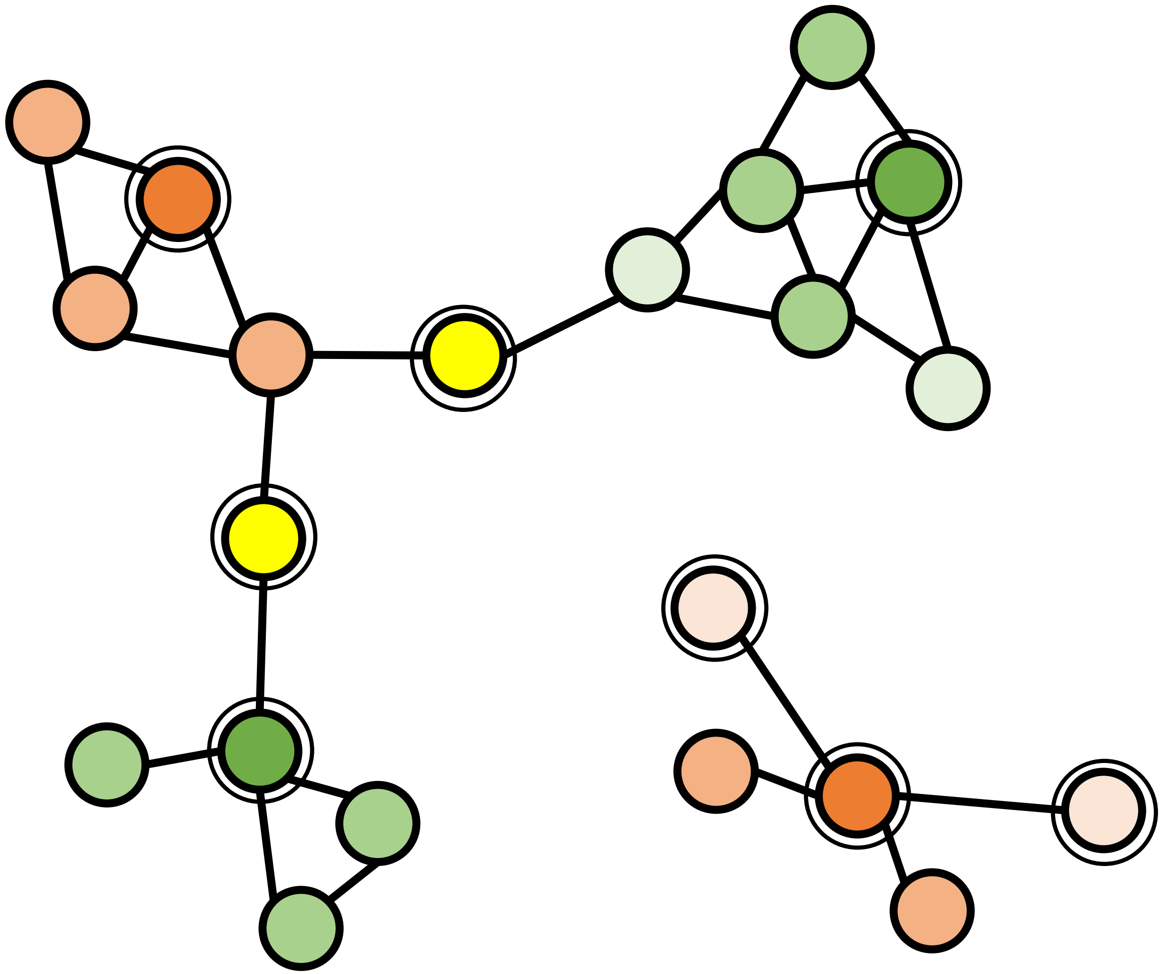

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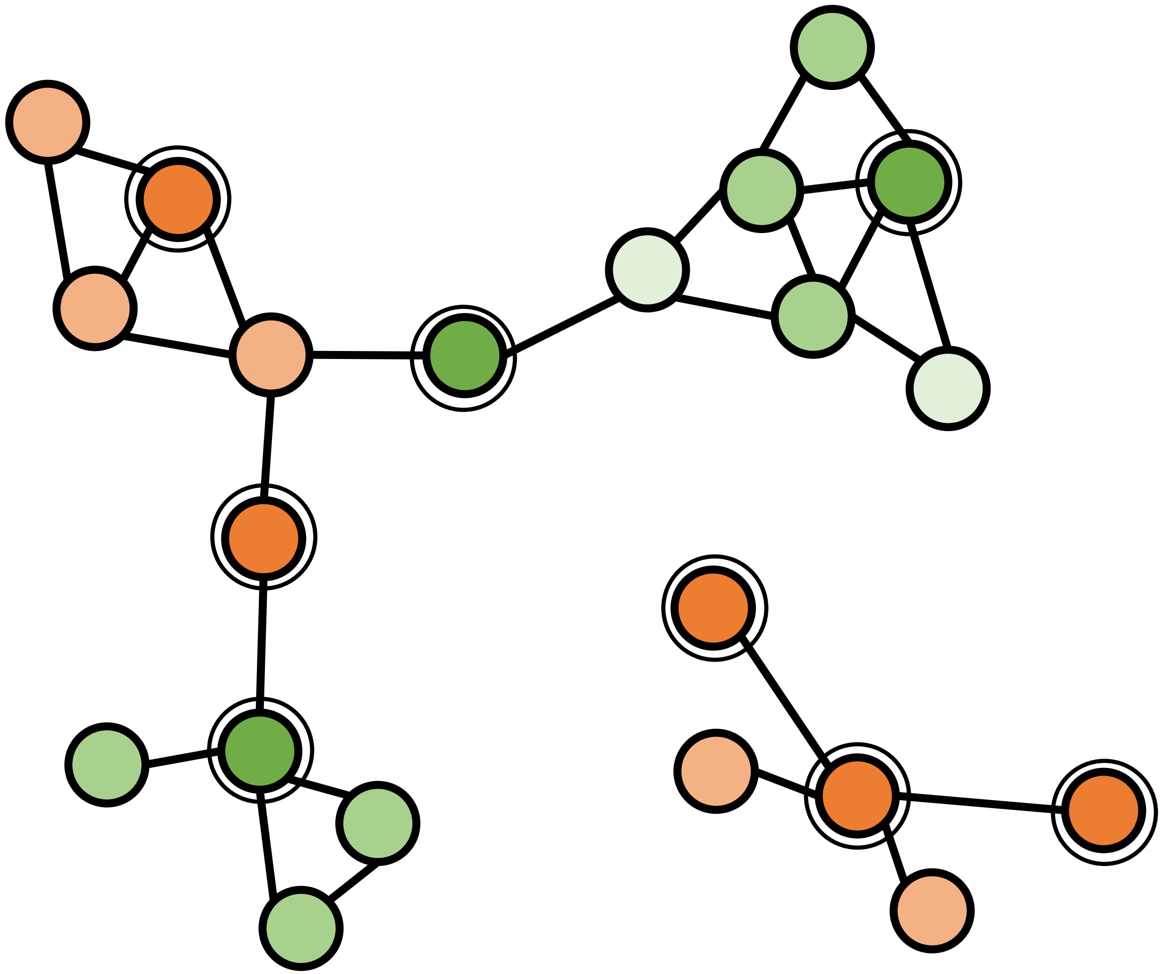

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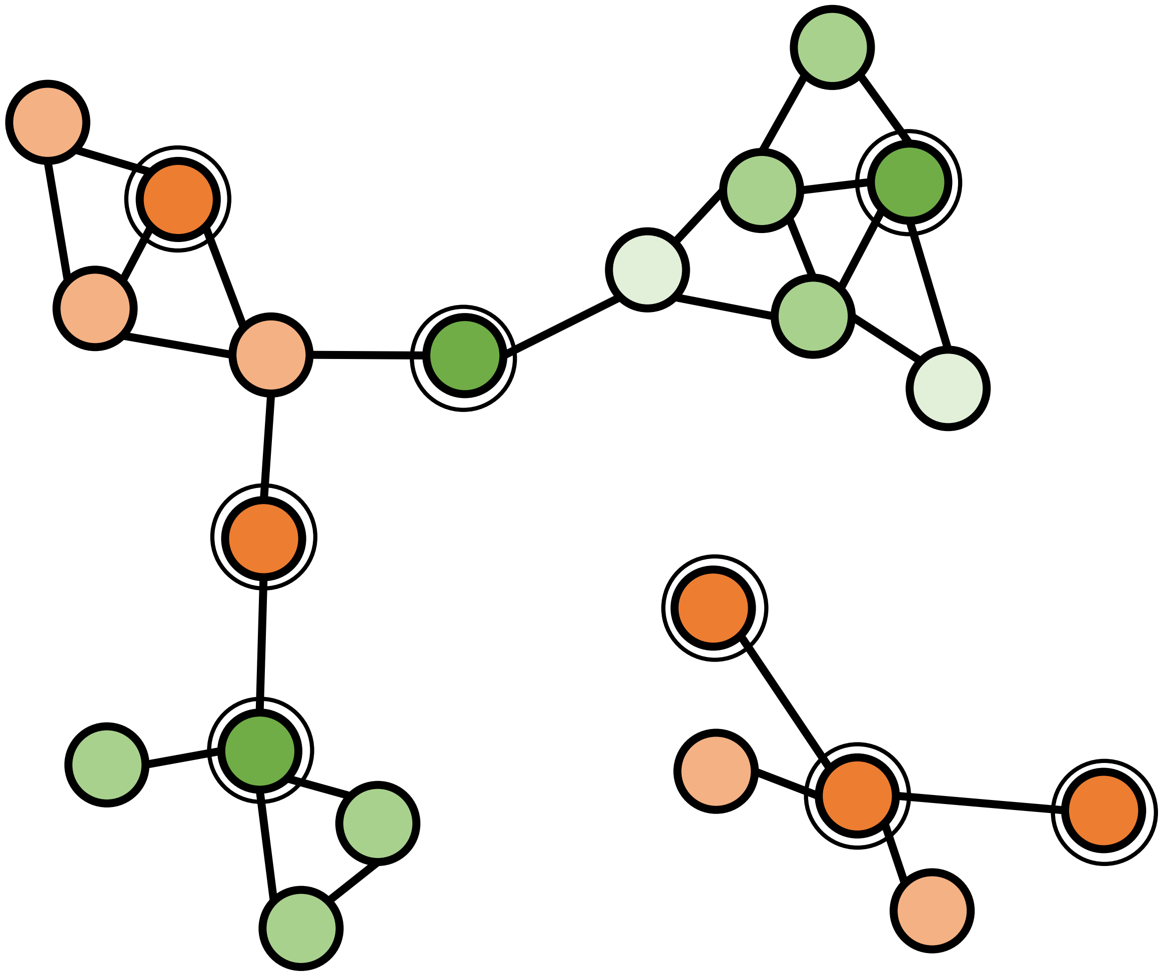

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- Query unlabelled data points that are “confused”
- Repeat!

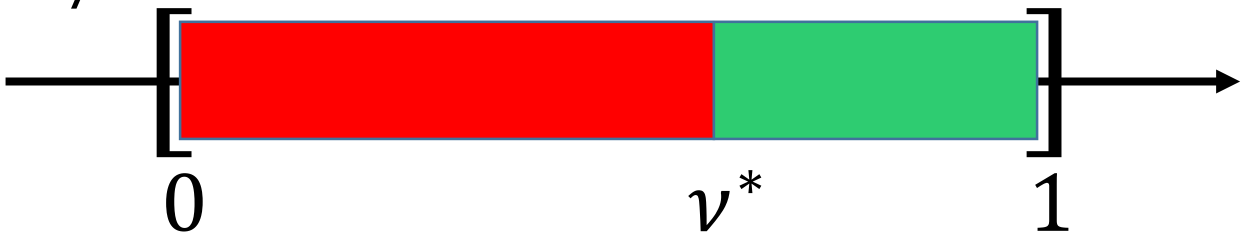
Active Learning Attempt II

Learning theoretic result

- To learn classifier with ϵ error, SVM/NN need $\mathcal{O}\left(\frac{1}{\epsilon}\right)$ labeled data pts
- Suppose data $S \subset [0,1]$ and true classifier is a threshold

$$y = 2 \cdot \mathbb{I}\{x \geq v^*\} - 1$$

- Notice that we can perform binary search to estimate v^*



- Let $a = 0, b = 1$
- For $t = 1,2, \ldots$
  - Query the label of the data point $(a+b)/2$
  - If label is -1 let $a \leftarrow (a+b)/2$ else let $b \leftarrow (a+b)/2$
  - If $b - a < \epsilon$, stop and output $\hat{v} = (a+b)/2$
- We queried only $\log(1/\epsilon)$ labels and yet ensured $|\hat{v} - v^*| < \epsilon$
- Exponential improvement in number of labelled samples needed!

Active Learning Attempt II

- This is the most simple form of *version space* search
- Search the space of all classifiers
  - In the previous example, classifiers corresponded to thresholds
- Can get tricky to do this efficiently even over linear classifiers
- Also tricky to handle cases that are not linearly separable
- Can't we do boosting or bagging to solve this problem?
- Yes, search for ActBoost (the name is lame but the algo isn't)

Active Learning

- Many other techniques to query labels
- If working with a Bayesian model, query data point whose predictive posterior variance is largest
- Query-by-committee – maintain a committee of several models and query data point on which committee disagrees the most
- Related concept of disagreement coefficient
- Expected model drift – maintain a single model but query the data point whose label, if known, will change the model the most

Semi-supervised Learning

Semi-supervision

- Labeled data is expensive since manual effort often involved
- Unlabelled data often free to obtain by crawling repo/www
- Why is unlabelled data of any use?
- Since it gives us valuable access to $\mathbb{P}[x]$
- If we have a super awesome model of $\mathbb{P}[x]$ then under some assumptions, a few labelled data points enough to learn $\mathbb{P}[y,x]$
- Assumptions?? Yes, SSL usually works by imposing a heavy inductive bias
  - Points deemed similar by blah notion of similarity have similar labels
  - Points in the same cluster given by blah clustering algo have same labels
  - Some assumption necessary to relate labelled and unlabelled data
- If assumption is inappropriate then SSL method suffers

SSL Attempt I – Generative Learning

- Labelled $L = \{x^i, y^i\}_{i=1,\ldots,n}$ and unlabeled data $U = \{x^j\}_{j=n+1,\ldots,n+m}$
- Learn a generative model Θ that models $\mathbb{P}[x]$ and $\mathbb{P}[y \mid x]$

$$\log \mathbb{P}[L \cup U \mid \Theta] = \log \mathbb{P}[L \mid \Theta] + \log \mathbb{P}[U \mid \Theta]$$

$$= \sum_{i=1}^{n} \log \mathbb{P}\left[y^i \mid x^i, \Theta\right] + \log \mathbb{P}\left[x^i \mid \Theta\right] + \sum_{j=n+1}^{n+m} \log \mathbb{P}\left[x^j \mid \Theta\right]$$

- Introduce latent variables $z^j \in [C]$ to model labels of points in U

$$= \sum_{i=1}^{n} \log \mathbb{P}\left[y^i \mid x^i, \Theta\right] + \log \mathbb{P}\left[x^i \mid \Theta\right] + \sum_{j=n+1}^{n+m} \log\left(\sum_{z^j=1}^{C} \mathbb{P}\left[z^j \mid x^j, \Theta\right] \cdot \mathbb{P}\left[x^j \mid \Theta\right]\right)$$

- Have fun executing the EM algorithm on this ☺

SSL Attempt II - Bootstrapping

- Basically the hard-assignment version for the previous slide
- Makes sense even in non-PML settings though
- Use any nice algo on L to learn a classifier f^0
- For $t = 1,2, \ldots$
  - Use f^{t-1} to label data points in U i.e. $z^{t,j} = f^{t-1}(x^j), j = n+1, \ldots,$
  - Use the nice algo on the dataset $L \cup \{x^j, z^{t,j}\}$ to learn f^t
  - Stop when tired
- Very simple to try out first before attempting more fancy methods
- Be careful – may reinforce wrong predictions
- No way to even detect if f^t getting better on U or not

SSL Attempt III - Regularization

- Incorporate a prior to force "similar" points to have similar labels
- Lets switch to a regression problem for simplicity
- Assume a notion of similarity between points $a_{ij} = K(x^i, x^j)$
  - Should not depend on the label i.e. can be computed over U as well
- Want $f(x^i)$ to be close to $f(x^j)$ if a_{ij} is large
- Can enforce this by asking $a_{ij} \cdot \left(f(x^i) - f(x^j)\right)^2$ to be small

$$\arg\min_f \sum_{i=1}^{n} \ell(f(x^i), y^i) + \sum_{i,j=1}^{m+n} a_{ij} \cdot \left(f(x^i) - f(x^j)\right)^2$$

- Can also incorporate a usual regularizer $r(f)$

SSL Attempt III - Regularization

- Incorporate a prior to force
- Lets switch to a regression
- Assume a notion of similarit
  - Should not depend on the lab
- Want $f(x^i)$ to be close to $f(x^j)$ i $_{ij}$ is large
- Can enforce this by asking $a_{ij} \cdot \left(f(x^i) - f(x^j)\right)^2$ to be small

$$\arg\min_{f} \sum_{i=1}^{n} \ell\left(f(x^i), y^i\right) + \sum_{i,j=1}^{m+n} a_{ij} \cdot \left(f(x^i) - f(x^j)\right)^2$$

- Can also incorporate a usual regularizer $r(f)$

If $f(\mathbf{x}) = \langle \mathbf{w}, \mathbf{x} \rangle$ and $r(\mathbf{w}) = \lambda \cdot \|\mathbf{w}\|_2^2$, then

$$\arg\min_{w} \sum_{i=1}^{n} \ell\left(\langle \mathbf{w}, \mathbf{x}^i \rangle, y^i\right) + \lambda \cdot \|\mathbf{w}\|_2^2 + \mathbf{w}^\top X L X^\top \mathbf{w}$$

where $X = [\mathbf{x}^1, \dots, \mathbf{x}^{m+n}] \in \mathbb{R}^{d \times (m+n)}$. Find L?

Additional regularization $\mathbf{w}^\top XLX^\top\mathbf{w}$. Overall regularization $\mathbf{w}^\top R\mathbf{w}$ where $R = XLX^\top + \lambda \cdot I$

ation

If $f(\mathbf{x}) = \langle \mathbf{w}, \mathbf{x} \rangle$ and $r(\mathbf{w}) = \lambda \cdot \|\mathbf{w}\|_2^2$, then

$$\arg\min_{w} \sum_{i=1}^{n} \ell(\langle \mathbf{w}, \mathbf{x}^i \rangle, y^i) + \lambda \cdot \|\mathbf{w}\|_2^2 + \mathbf{w}^\top XLX^\top \mathbf{w}$$

where $X = [\mathbf{x}^1, \ldots, \mathbf{x}^{m+n}] \in \mathbb{R}^{d\times(m+n)}$. Find L?

- Incorporate a prior to force
- Lets switch to a regression p
- Assume a notion of similarit
  - Should not depend on the lab
- Want $f(x^i)$ to be close to $f(x^j)$ i $_{ij}$ is large
- Can enforce this by asking $a_{ij} \cdot \left(f(x^i) - f(x^j)\right)^2$ to be small

$$\arg\min_{f} \sum_{i=1}^{n} \ell(f(x^i), y^i) + \sum_{i,j=1}^{m+n} a_{ij} \cdot \left(f(x^i) - f(x^j)\right)^2$$

- Can also incorporate a usual regularizer $r(f)$

SSL Attempt IV – Transductive SVM

- Transduction is a special form of learning where test features are used to train the model – note, test labels still taboo to look at
- However, the "transductive" SVM works in SSL settings too
- Minimizes hinge loss on labelled points and keeps unlabelled points away from the hyperplane on at least one side

$$\min_{\mathbf{w},\{\xi_i\}} \frac{1}{2}\|\mathbf{w}\|_2^2 + \sum_{i=1}^{m+n} \xi_i$$

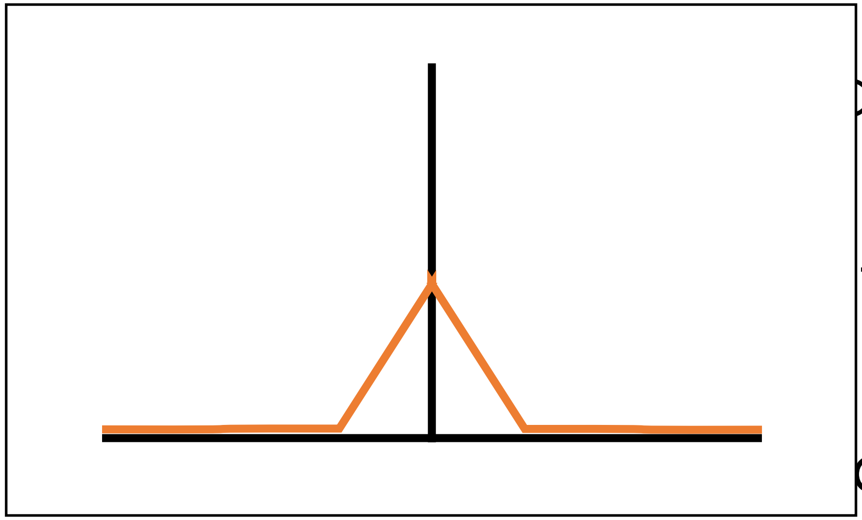
$$y^i \cdot \langle \mathbf{w}, \mathbf{x}^i \rangle \geq 1 - \xi_i, i = 1, \ldots, n$$

$$|\langle \mathbf{w}, \mathbf{x}^j \rangle| \geq 1 - \xi_j, j = n+1, \ldots, m+n$$

$$\xi_i \geq 0, i = 1, \ldots, n, n+1, \ldots, m+n$$

- Results in a non-convex optimization problem – difficult to solve

SSL Attempt IV – Transductive SVM



- al for
  – no
- tive" SVM
- label points an
  ane on at least on

Can show that for unlabelled points, TSVM uses the symmetric hinge loss function $\ell(\mathbf{w}, \mathbf{x}^j) = \min\{[1 - \langle \mathbf{w}, \mathbf{x}^j \rangle]_+, [1 + \langle \mathbf{w}, \mathbf{x}^j \rangle]_+\}$

Note that if $|\langle \mathbf{w}, \mathbf{x}^j \rangle| \geq 1 - \xi_j$ then $z^j \cdot \langle \mathbf{w}, \mathbf{x}^j \rangle \geq 1 - \xi_j$ for either $z^j = 1$ or $z^j = -1$

$$\min_{\mathbf{w}, \{\xi_i\}} \frac{1}{2}\|\mathbf{w}\|_2^2 + \sum_{i=1}^{m+n} \xi_i$$

$$y^i \cdot \langle \mathbf{w}, \mathbf{x}^i \rangle \geq 1 - \xi_i, i = 1, \ldots, n$$

$$|\langle \mathbf{w}, \mathbf{x}^j \rangle| \geq 1 - \xi_j, j = n+1, \ldots, m+n$$

$$\xi_i \geq 0, i = 1, \ldots, n, n+1, \ldots, m+n$$

- Results in a non-convex optimization problem – difficult to solve

SSL Attempt IV – Transductive SVM

Exercise: show TSVM actually solves

$$\min_{\mathbf{w},\{\xi_i\},\{z^j\}} \frac{1}{2}\|\mathbf{w}\|_2^2 + \sum_{i=1}^{m+n} \xi_i$$

$$y^i \cdot \langle \mathbf{w}, \mathbf{x}^i \rangle \geq 1 - \xi_i, i = 1, \ldots, n$$

$$z^j \cdot \langle \mathbf{w}, \mathbf{x}^j \rangle \geq 1 - \xi_j, j = n+1, \ldots, m+n$$

$$\xi_i \geq 0, i = 1, \ldots, m+n$$

$$z^j \in \{-1, +1\}, j = n+1, \ldots, m+n$$

i.e. jointly optimizes latent vars and model

points, TSVM
ss function
$+ \langle \mathbf{w}, \mathbf{x}^j \rangle]_+\}$

$, \mathbf{x}^j \rangle| \geq 1 - \xi_j$
$\rangle \geq 1 - \xi_j$ for
or $z^j = -1$

$$|\langle \mathbf{w}, \mathbf{x}^j \rangle| \geq 1 - \xi_j, j = n + 1, \ldots, m + n$$

$$\xi_i \geq 0, i = 1, \ldots, n, n + 1,$$

- Results in a non-convex optimization p

Bootstrapping using an SVM would have solved the same problem using hard AltMin

Time to Wrap Up!

A whirlwind tour of topics we did not discuss

Many topics we did not cover

- Bayesian learning (applicable to several problem areas – CS775)
- Graphical models (model interactions within data feat. - CS772)
- Transfer learning (when exam syllabus may have a "drift")
- Reinforcement learning (learn from an evolving teacher – CS773)
- Multi-task learning (solve several problems on the same data)
- Multi-view learning (different feature rep. of the same data)
- Sparse recovery (learn space-efficient models – CS772/CS777)
- Time series modelling (HMMs, AR, ARMA, RNNs)
- Learning theory (provable goodness of learnt models – CS777)
- Learning on data streams (experts, bandits – CS773)
- Advanced Optimization Techniques (CS774/CS777)

Please give your Feedback

http://tinyurl.com/ml17-18afb