Apache Big Data Seville 2016

Apache SystemML™

Apache SystemML
Declarative Machine Learning

Luciano Resende
IBM | Spark Technology Center

About Me

Apache SystemML™

Luciano Resende (lresende@apache.org)

- Architect and community liaison at IBM – Spark Technology Center
- Have been contributing to open source at ASF for over 10 years
- Currently contributing to : Apache Bahir, Apache Spark, Apache Zeppelin and Apache SystemML (incubating) projects


@lresende1975


lresende

http://lresende.blogspot.com/


http://slideshare.net/luckbr1975

https://www.linkedin.com/in/lresende

Origins of the SystemML Project

2007-2008: Multiple projects at IBM Research – Almaden involving machine learning on Hadoop.

2009: A dedicated team for scalable ML was created.

2009-2010: Through engagements with customers, we observe how data scientists create machine learning algorithms.

State-of-the-Art: Small Data

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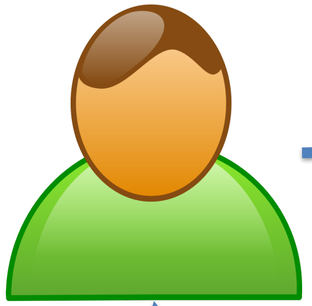
Data Scientist



```
X = read ($X);   # explanatory variables
y = read ($Y);   # predicted variables

n = nrow (X);
m = ncol (X);

# Rescale the columns of X if needed
scale_lambda = matrix (1, rows = 1, cols = m);
lambda = t(scale_lambda) * $reg;

# Constr[illegible] apply[illegible] equation
A = t(X) [illegible] X + [illegible] lambda)
b = t(X) [illegible] y;

beta = solve (A, b);
...
write (beta, $B);
```

R or Python

Weather station data 2005

Weather station	Average temperatures (°C)	Min	Mean	Max	Daily rainfall (mm)	Mean	Max
RYGGE		−10.5	7.5	23.8		2.0	34.8
NESBYEN - TODOKK		−16.8	4.8	21.8		1.2	35.9
TORUNGEN FYR		−6.0	8.5	21.8		2.1	35.9
SOLA		−4.6	8.5	19.7		3.6	48.1
GARDERMOEN		−15.4	5.4	19.4		2.0	48.5
BERGEN - FLORIDA		[illegible]	[illegible]	[illegible]		8.4	156.5
LÆRDAL - MOLDO		[illegible]	[illegible]	[illegible]		1.8	58.1
TAFJORD		[illegible]	[illegible]	[illegible]		3.2	64.5
VÆRNES		[illegible]	[illegible]	[illegible]		2.5	37.0
RENA - HAUGEDALEN		[illegible]	[illegible]	[illegible]		1.9	26.6
BODO VI		−8.2	5.7	22.1		4.0	39.5
TROMSO		−8.4	4.1	19.3		3.5	38.5
KAUTOKEINO		−29.9	−0.5	21.1		1.5	18.8
NY-ÅLESUND		−24.4	−3.4	13.2		0.9	29.1
JAN MAYEN		−11.6	0.6	11.1		2.0	23.3

Data

Personal Computer

24	AAPL	30/05/2008	182.75	188.75
25	AAPL	06/06/2008	188.6	185.64
26	AAPL	13/06/2008	184.79	172.37
27	AAPL	20/06/2008	171.3	175.27
28	AAPL	27/06/2008	[illegible]74	170.09
29	AAPL	03/[illegible]/2008	[illegible]9	170.12
30	AAPL	[illegible]/07/2008	[illegible]15	172.58
31	AAPL	[illegible]/07/2008	[illegible]24	165.15
32	AAPL	25/07/2008	[illegible]3	162.12
33	AAPL	01/08/2008	162.34	156.66
34	AAPL	08/08/2008	156.6	169.55
35	AAPL	15/08/2008	170.07	175.74
36	AAPL	22/08/2008	175.57	176.79
37	AAPL	29/08/2008	176.15	169.53

Results

State-of-the-Art: Big Data

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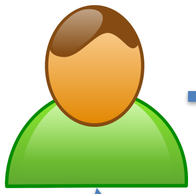
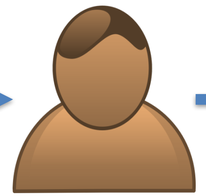
Data Scientist

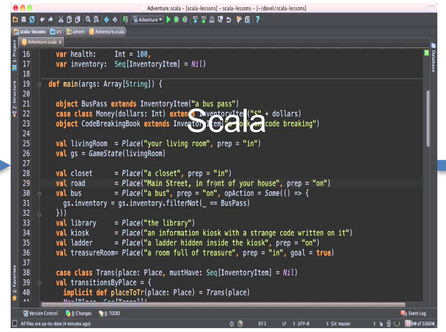
Systems Programmer



```
X = read ($X);   # explanatory variables
y = read ($Y);   # predicted variables

n = nrow (X);
m = ncol (X);

# Rescale the columns of X if needed
scale_lambda = matrix (1, rows = 1, cols = m);
lambda = t(scale_lambda) * $reg;

# Construct and solve system of equations
A = t(X) %*% X + diag (lambda);
b = t(X) %*% y;

beta = solve (A, b);
...
write (beta, $B);
```

R or Python





```
var health:    Int = 100,
var inventory: Seq[InventoryItem] = Nil)

def main(args: Array[String]) {

  object BusPass extends InventoryItem("a bus pass")
  case class Money(dollars: Int) extends InventoryItem(dollars + " dollars")
  object CodeBreakingBook extends InventoryItem("a book on code breaking")

  val livingRoom  = Place("your living room", prep = "in")
  val gs = GameState(livingRoom)

  val closet      = Place("a closet", prep = "in")
  val road        = Place("Main Street, in front of your house", prep = "on")
  val bus         = Place("a bus", prep = "on", opAction = Some(() => {
    gs.inventory = gs.inventory.filterNot(_ == BusPass)
  }))
  val library     = Place("the library")
  val kiosk       = Place("an information kiosk with a strange code written on it")
  val ladder      = Place("a ladder hidden inside the kiosk", prep = "on")
  val treasureRoom= Place("a room full of treasure", prep = "in", goal = true)

  case class Trans(place: Place, mustHave: Seq[InventoryItem] = Nil)
  val transitionsByPlace = {
    implicit def placeToTr(place: Place) = Trans(place)
```

Scala

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Results

State-of-the-Art: Big Data

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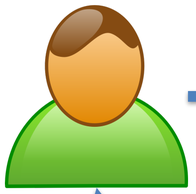
Systems



- Days or weeks per iteration
- Errors while translating algorithms

Spark

Results

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The SystemML Vision

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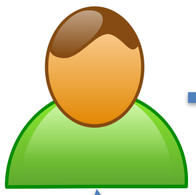
Data Scientist



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lambda = t(scale_lambda) * $reg;

# Construct and solve system of equations
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b = t(X) %*% y;

beta = solve (A, b);
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write (beta, $B);
```

R or Python

SystemML

Spark

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Results

The SystemML Vision

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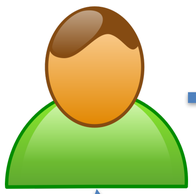
Data Scientist

😀 Fast iteration

😀 Same answer



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m = ncol (X);

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lambda = t(scale_lambda) * $reg;

# Construct and solve system of equations
A = t(X) %*% X + diag (lambda);
b = t(X) %*% y;

beta = solve (A, b);
...
write (beta, $B);
```

R or Python

SystemML

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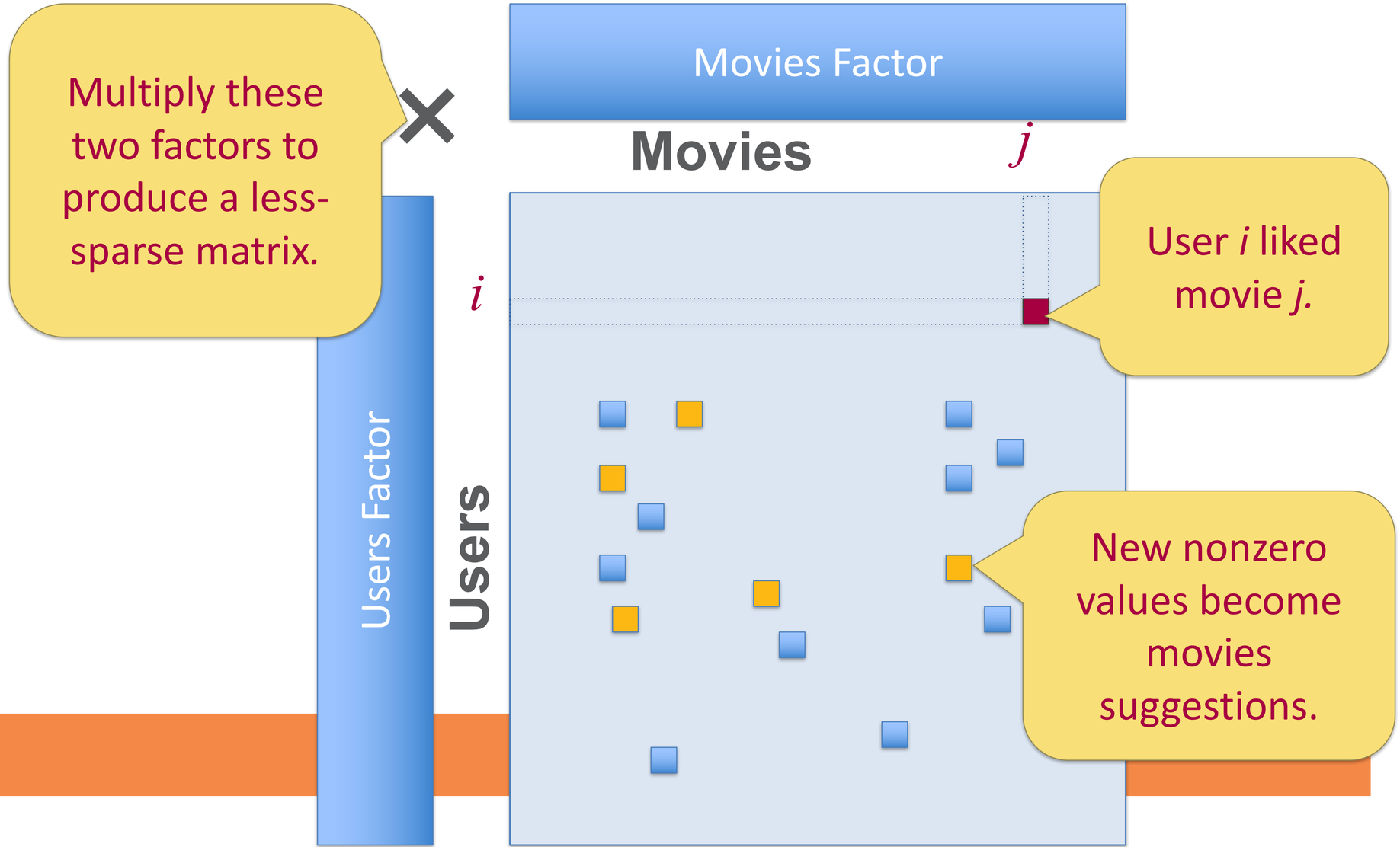
Results

Running Example:

Alternating Least Squares

Problem: Movie Recommendations



Alternating Least Squares (in R)

Apache SystemML™

```
U = rand(nrow(X), r, min = -1.0, max = 1.0);
V = rand(r, ncol(X), min = -1.0, max = 1.0);
while(i < mi) {
   i = i + 1; ii = 1;
   if (is_U)
      G = (W * (U %*% V - X)) %*% t(V) + lambda * U;
   else
      G = t(U) %*% (W * (U %*% V - X)) + lambda * V;
   norm_G2 = sum(G ^ 2); norm_R2 = norm_G2;
   R = -G; S = R;
   while(norm_R2 > 10E-9 * norm_G2 & ii <= mii) {
     if (is_U) {
       HS = (W * (S %*% V)) %*% t(V) + lambda * S;
       alpha = norm_R2 / sum (S * HS);
       U = U + alpha * S;
     } else {
       HS = t(U) %*% (W * (U %*% S)) + lambda * S;
       alpha = norm_R2 / sum (S * HS);
       V = V + alpha * S;
     }
     R = R - alpha * HS;
     old_norm_R2 = norm_R2; norm_R2 = sum(R ^ 2);
     S = R + (norm_R2 / old_norm_R2) * S;
     ii = ii + 1;
   }
   is_U = ! is_U;
}
```

Alternating Least Squares (in R)

Apache SystemML™

```
U = rand(nrow(X), r, min = -1.0, max = 1.0);                    1
V = rand(r, ncol(X), min = -1.0, max = 1.0);
while(i < mi) {                                                 4
  i = i + 1; ii = 1;
  if (is_U)
    G = (W * (U %*% V - X)) %*% t(V) + lambda * U;              2
  else
    G = t(U) %*% (W * (U %*% V - X)) + lambda * V;              3
  norm_G2 = sum(G ^ 2); norm_R2 = norm_G2;
  R = -G; S = R;
  while(norm_R2 > 10E-9 * norm_G2 & ii <= mii) {                4
    if (is_U) {
      HS = (W * (S %*% V)) %*% t(V) + lambda * S;
      alpha = norm_R2 / sum(S * HS);                            2
      U = U + alpha * S;
    } else {
      HS = t(U) %*% (W * (U %*% S)) + lambda * S;
      alpha = norm_R2 / sum(S * HS);                            3
      V = V + alpha * S;
    }
    R = R - alpha * HS;
    old_norm_R2 = norm_R2; norm_R2 = sum(R ^ 2);
    S = R + (norm_R2 / old_norm_R2) * S;
    ii = ii + 1;                                                4
  }
  is_U = ! is_U;
}
```

1. Start with random factors.
2. Hold the **Movies** factor constant and find the best value for the **Users** factor.

   (Value that most closely approximates the original matrix)
3. Hold the **Users** factor constant and find the best value for the **Movies** factor.
4. Repeat steps 2-3 until convergence.

Every line has a clear purpose!

Alternating Least Squares (spark.ml)

Apache SystemML™

```scala
/**
 * :: DeveloperApi ::
 * Implementation of the ALS algorithm.
 */
@DeveloperApi
def train[ID: ClassTag]( // scalastyle:ignore
    ratings: RDD[Rating[ID]],
    rank: Int = 10,
    numUserBlocks: Int = 10,
    numItemBlocks: Int = 10,
    maxIter: Int = 10,
    regParam: Double = 1.0,
    implicitPrefs: Boolean = false,
    alpha: Double = 1.0,
    nonnegative: Boolean = false,
    intermediateRDDStorageLevel: StorageLevel = StorageLevel.MEMORY_AND_DISK,
    finalRDDStorageLevel: StorageLevel = StorageLevel.MEMORY_AND_DISK,
    checkpointInterval: Int = 10,
    seed: Long = 0L)(
    implicit ord: Ordering[ID]): (RDD[(ID, Array[Float])], RDD[(ID, Array[Float])]) = {
  require(intermediateRDDStorageLevel != StorageLevel.NONE,
    "ALS is not designed to run without persisting intermediate RDDs.")
  val sc = ratings.sparkContext
  val userPart = new ALSPartitioner(numUserBlocks)
  val itemPart = new ALSPartitioner(numItemBlocks)
  val userLocalIndexEncoder = new LocalIndexEncoder(userPart.numPartitions)
  val itemLocalIndexEncoder = new LocalIndexEncoder(itemPart.numPartitions)
  val solver = if (nonnegative) new NNLSSolver else new CholeskySolver
  val blockRatings = partitionRatings(ratings, userPart, itemPart)
    .persist(intermediateRDDStorageLevel)
  val (userInBlocks, userOutBlocks) =
    makeBlocks("user", blockRatings, userPart, itemPart, intermediateRDDStorageLevel)
  // materialize blockRatings and user blocks
  userOutBlocks.count()
  val swappedBlockRatings = blockRatings.map {
    case ((userBlockId, itemBlockId), RatingBlock(userIds, itemIds, localRatings)) =>
      ((itemBlockId, userBlockId), RatingBlock(itemIds, userIds, localRatings))
  }
  val (itemInBlocks, itemOutBlocks) =
    makeBlocks("item", swappedBlockRatings, itemPart, userPart, intermediateRDDStorageLevel)
  // materialize item blocks
  itemOutBlocks.count()
  val seedGen = new XORShiftRandom(seed)
  var userFactors = initialize(userInBlocks, rank, seedGen.nextLong())
  var itemFactors = initialize(itemInBlocks, rank, seedGen.nextLong())
  var previousCheckpointFile: Option[String] = None
  val shouldCheckpoint: Int => Boolean = (iter) =>
    sc.checkpointDir.isDefined && checkpointInterval != -1 && (iter % checkpointInterval == 0)
  val deletePreviousCheckpointFile: () => Unit = () =>
    previousCheckpointFile.foreach { file =>
      try {
        FileSystem.get(sc.hadoopConfiguration).delete(new Path(file), true)
      } catch {
        case e: IOException =>
          logWarning(s"Cannot delete checkpoint file $file:", e)
      }
    }
```

```scala
    srcIds += r.user
    dstIds += r.item
    ratings += r.rating
    this
  }

  /** Merges another [[RatingBlockBuilder]]. */
  def merge(other: RatingBlock[ID]): this.type = {
    size += other.srcIds.length
    srcIds ++= other.srcIds
    dstIds ++= other.dstIds
    ratings ++= other.ratings
    this
  }

  /** Builds a [[RatingBlock]]. */
  def build(): RatingBlock[ID] = {
    RatingBlock[ID](srcIds.result(), dstIds.result(), ratings.result())
  }
}

/**
 * Partitions raw ratings into blocks.
 *
 * @param ratings raw ratings
 * @param srcPart partitioner for src IDs
 * @param dstPart partitioner for dst IDs
 *
 * @return an RDD of rating blocks in the form of ((srcBlockId, dstBlockId), ratingBlock)
 */
private def partitionRatings[ID: ClassTag](
    ratings: RDD[Rating[ID]],
    srcPart: Partitioner,
    dstPart: Partitioner): RDD[((Int, Int), RatingBlock[ID])] = {

  /* The implementation produces the same result as the following but generates less objec

  ratings.map { r =>
    ((srcPart.getPartition(r.user), dstPart.getPartition(r.item)), r)
  }.aggregateByKey(new RatingBlockBuilder)(
      seqOp = (b, r) => b.add(r),
      combOp = (b0, b1) => b0.merge(b1.build()))
    .mapValues(_.build())
  */

  val numPartitions = srcPart.numPartitions * dstPart.numPartitions
  ratings.mapPartitions { iter =>
    val builders = Array.fill(numPartitions)(new RatingBlockBuilder[ID])
    iter.flatMap { r =>
      val srcBlockId = srcPart.getPartition(r.user)
      val dstBlockId = dstPart.getPartition(r.item)
      val idx = srcBlockId + srcPart.numPartitions * dstBlockId
      val builder = builders(idx)
      builder.add(r)
      if (builder.size >= 2048) { // 2048 * (3 * 4) = 24k
        builders(idx) = new RatingBlockBuilder
        Iterator.single(((srcBlockId, dstBlockId), builder.build()))
```

```scala
      } else {
        Iterator.empty
      }
    } ++ {
      builders.view.zipWithIndex.filter(_._1.size > 0).map { case (block, idx) =>
        val srcBlockId = idx % srcPart.numPartitions
        val dstBlockId = idx / srcPart.numPartitions
        ((srcBlockId, dstBlockId), block.build())
      }
    }
  }.groupByKey().mapValues { blocks =>
    val builder = new RatingBlockBuilder[ID]
    blocks.foreach(builder.merge)
    builder.build()
  }.setName("ratingBlocks")
}

/**
 * Builder for uncompressed in-blocks of (srcId, dstEncodedIndex, rating) tuples.
 * @param encoder encoder for dst indices
 */
private[recommendation] class UncompressedInBlockBuilder[@specialized(Int, Long) ID: ClassTag](
    encoder: LocalIndexEncoder)(
    implicit ord: Ordering[ID]) {

  private val srcIds = mutable.ArrayBuilder.make[ID]
  private val dstEncodedIndices = mutable.ArrayBuilder.make[Int]
  private val ratings = mutable.ArrayBuilder.make[Float]

  /**
   * Adds a dst block of (srcId, dstLocalIndex, rating) tuples.
   *
   * @param dstBlockId dst block ID
   * @param srcIds original src IDs
   * @param dstLocalIndices dst local indices
   * @param ratings ratings
   */
  def add(
      dstBlockId: Int,
      srcIds: Array[ID],
      dstLocalIndices: Array[Int],
      ratings: Array[Float]): this.type = {
    val sz = srcIds.length
    require(dstLocalIndices.length == sz)
    require(ratings.length == sz)
    this.srcIds ++= srcIds
    this.ratings ++= ratings
    var j = 0
    while (j < sz) {
      this.dstEncodedIndices += encoder.encode(dstBlockId, dstLocalIndices(j))
      j += 1
    }
    this
  }

  /** Builds a [[UncompressedInBlock]]. */
  def build(): UncompressedInBlock[ID] = {
```

Alternating Least Squares (spark.ml)

Apache SystemML™

```
if (implicitPrefs) {
  for (iter <- 1 to maxIter) {
    userFactors.setName(s"userFactors-$iter").persist(intermediateRDDStorageLevel)
    val previousItemFactors = itemFactors
    itemFactors = computeFactors(userFactors, userOutBlocks, itemInBlocks, rank, regParam
      userLocalIndexEncoder, implicitPrefs, alpha, solver)
    previousItemFactors.unpersist()
    itemFactors.setName(s"itemFactors-$iter").persist(intermediateRDDStorageLevel)
    // TODO: Generalize PeriodicGraphCheckpointer and use it here.
    if (shouldCheckpoint(iter)) {
      itemFactors.checkpoint() // itemFactors gets materialized in computeFactors.
    }
    val previousUserFactors = userFactors
    userFactors = computeFactors(itemFactors, itemOutBlocks, userInBlocks, rank, regParam
      itemLocalIndexEncoder, implicitPrefs, alpha, solver)
    if (shouldCheckpoint(iter)) {
      deletePreviousCheckpointFile()
      previousCheckpointFile = itemFactors.getCheckpointFile
    }
    previousUserFactors.unpersist()
  }
} else {
  for (iter <- 0 until maxIter) {
    itemFactors = computeFactors(userFactors, userOutBlocks, itemInBlocks, rank, regParam
      userLocalIndexEncoder, solver = solver)
    if (shouldCheckpoint(iter)) {
      itemFactors.checkpoint()
      itemFactors.count() // checkpoint item factors and cut lineage
      deletePreviousCheckpointFile()
      previousCheckpointFile = itemFactors.getCheckpointFile
    }
    userFactors = computeFactors(itemFactors, itemOutBlocks, userInBlocks, rank, regParam
      itemLocalIndexEncoder, solver = solver)
  }
}
val userIdAndFactors = userInBlocks
  .mapValues(_.srcIds)
  .join(userFactors)
  .mapPartitions({ items =>
    items.flatMap { case (_, (ids, factors)) =>
      ids.view.zip(factors)
    }
  // Preserve the partitioning because IDs are consistent with the partitioners in userI
  // and userFactors.
  }, preservesPartitioning = true)
  .setName("userFactors")
  .persist(finalRDDStorageLevel)
val itemIdAndFactors = itemInBlocks
  .mapValues(_.srcIds)
  .join(itemFactors)
  .mapPartitions({ items =>
    items.flatMap { case (_, (ids, factors)) =>
      ids.view.zip(factors)
    }
  }, preservesPartitioning = true)
  .setName("itemFactors")
  .persist(finalRDDStorageLevel)
  if (finalRDDStorageLevel != StorageLevel.NONE) {
    userIdAndFactors.count()
    itemFactors.unpersist()
    itemIdAndFactors.count()
    userInBlocks.unpersist()
    userOutBlocks.unpersist()
    itemInBlocks.unpersist()
    itemOutBlocks.unpersist()
    blockRatings.unpersist()
  }
  (userIdAndFactors, itemIdAndFactors)
}

/**
 * Factor block that stores factors (Array[Float]) in an Array.
 */
private type FactorBlock = Array[Array[Float]]

/**
 * Out-link block that stores, for each dst (item/user) block, which src (user/item) factors to
 * send. For example, outLinkBlock(0) contains the local indices (not the original src IDs) of t
 * src factors in this block to send to dst block 0.
 */
private type OutBlock = Array[Array[Int]]

/**
 * In-link block for computing src (user/item) factors. This includes the original src IDs
 * of the elements within this block as well as encoded dst (item/user) indices and correspondir
 * ratings. The dst indices are in the form of (blockId, localIndex), which are not the original
 * dst IDs. To compute src factors, we expect receiving dst factors that match the dst indices.
 * For example, if we have an in-link record
 *
 * {srcId: 0, dstBlockId: 2, dstLocalIndex: 3, rating: 5.0},
 *
 * and assume that the dst factors are stored as dstFactors: Map[Int, Array[Array[Float]]], whic
 * is a blockId to dst factors map, the corresponding dst factor of the record is dstFactor(2)(3
 *
 * We use a CSC-like (compressed sparse column) format to store the in-link information. So we c
 * compute src factors one after another using only one normal equation instance.
 *
 * @param srcIds src ids (ordered)
 * @param dstPtrs dst pointers. Elements in range [dstPtrs(i), dstPtrs(i+1)) of dst indices and
 *                ratings are associated with srcIds(i).
 * @param dstEncodedIndices encoded dst indices
 * @param ratings ratings
 *
 * @see [[LocalIndexEncoder]]
 */
private[recommendation] case class InBlock[@specialized(Int, Long) ID: ClassTag](
    srcIds: Array[ID],
    dstPtrs: Array[Int],
    dstEncodedIndices: Array[Int],
    ratings: Array[Float]) {
  /** Size of the block. */
  def size: Int = ratings.length
  require(dstEncodedIndices.length == size)
  require(dstPtrs.length == srcIds.length + 1)
}

/**
 * Initializes factors randomly given the in-link blocks.
 *
 * @param inBlocks in-link blocks
 * @param rank rank
 * @return initialized factor blocks
 */
private def initialize[ID](
    inBlocks: RDD[(Int, InBlock[ID])],
    rank: Int,
    seed: Long): RDD[(Int, FactorBlock)] = {
  // Choose a unit vector uniformly at random from the unit sphere, but from the
  // "first quadrant" where all elements are nonnegative. This can be done by choosing
  // elements distributed as Normal(0,1) and taking the absolute value, and then normalizing.
  // This appears to create factorizations that have a slightly better reconstruction
  // (<1%) compared picking elements uniformly at random in [0,1].
  inBlocks.map { case (srcBlockId, inBlock) =>
    val random = new XORShiftRandom(byteswap64(seed ^ srcBlockId))
    val factors = Array.fill(inBlock.srcIds.length) {
      val factor = Array.fill(rank)(random.nextGaussian().toFloat)
      val nrm = blas.snrm2(rank, factor, 1)
      blas.sscal(rank, 1.0f / nrm, factor, 1)
      factor
    }
    (srcBlockId, factors)
  }
}

/**
 * A rating block that contains src IDs, dst IDs, and ratings, stored in primitive arrays.
 */
private[recommendation] case class RatingBlock[@specialized(Int, Long) ID: ClassTag](
    srcIds: Array[ID],
    dstIds: Array[ID],
    ratings: Array[Float]) {
  /** Size of the block. */
  def size: Int = srcIds.length
  require(dstIds.length == srcIds.length)
  require(ratings.length == srcIds.length)
}

/**
 * Builder for [[RatingBlock]]. [[mutable.ArrayBuilder]] is used to avoid boxing/unboxing.
 */
private[recommendation] class RatingBlockBuilder[@specialized(Int, Long) ID: ClassTag]
  extends Serializable {

  private val srcIds = mutable.ArrayBuilder.make[ID]
  private val dstIds = mutable.ArrayBuilder.make[ID]
  private val ratings = mutable.ArrayBuilder.make[Float]
  var size = 0

  /** Adds a rating. */
  def add(r: Rating[ID]): this.type = {
    size += 1
```

Alternating Least Squares (spark.ml)

Apache SystemML™

```
    new UncompressedInBlock(srcIds.result(), dstEncodedIndices.result(), ratings.result())
  }
}

/**
 * A block of (srcId, dstEncodedIndex, rating) tuples stored in primitive arrays.
 */
private[recommendation] class UncompressedInBlock[@specialized(Int, Long) ID: ClassTag](
    val srcIds: Array[ID],
    val dstEncodedIndices: Array[Int],
    val ratings: Array[Float])(
    implicit ord: Ordering[ID]) {

  /** Size the of block. */
  def length: Int = srcIds.length

  /**
   * Compresses the block into an [[InBlock]]. The algorithm is the same as converting a
   * sparse matrix from coordinate list (COO) format into compressed sparse column (CSC) format.
   * Sorting is done using Spark's built-in Timsort to avoid generating too many objects.
   */
  def compress(): InBlock[ID] = {
    val sz = length
    assert(sz > 0, "Empty in-link block should not exist.")
    sort()
    val uniqueSrcIdsBuilder = mutable.ArrayBuilder.make[ID]
    val dstCountsBuilder = mutable.ArrayBuilder.make[Int]
    var preSrcId = srcIds(0)
    uniqueSrcIdsBuilder += preSrcId
    var curCount = 1
    var i = 1
    var j = 0
    while (i < sz) {
      val srcId = srcIds(i)
      if (srcId != preSrcId) {
        uniqueSrcIdsBuilder += srcId
        dstCountsBuilder += curCount
        preSrcId = srcId
        j += 1
        curCount = 0
      }
      curCount += 1
      i += 1
    }
    dstCountsBuilder += curCount
    val uniqueSrcIds = uniqueSrcIdsBuilder.result()
    val numUniqueSrdIds = uniqueSrcIds.length
    val dstCounts = dstCountsBuilder.result()
    val dstPtrs = new Array[Int](numUniqueSrdIds + 1)
    var sum = 0
    i = 0
    while (i < numUniqueSrdIds) {
      sum += dstCounts(i)
      i += 1
      dstPtrs(i) = sum
    }
    InBlock(uniqueSrcIds, dstPtrs, dstEncodedIndices, ratings)
  }

  private def sort(): Unit = {
    val sz = length
    // Since there might be interleaved log messages, we insert a unique id for easy pairing.
    val sortId = Utils.random.nextInt()
    logDebug(s"Start sorting an uncompressed in-block of size $sz. (sortId = $sortId)")
    val start = System.nanoTime()
    val sorter = new Sorter(new UncompressedInBlockSort[ID])
    sorter.sort(this, 0, length, Ordering[KeyWrapper[ID]])
    val duration = (System.nanoTime() - start) / 1e9
    logDebug(s"Sorting took $duration seconds. (sortId = $sortId)")
  }
}

/**
 * A wrapper that holds a primitive key.
 *
 * @see [[UncompressedInBlockSort]]
 */
private class KeyWrapper[@specialized(Int, Long) ID: ClassTag](
    implicit ord: Ordering[ID]) extends Ordered[KeyWrapper[ID]] {

  var key: ID = _

  override def compare(that: KeyWrapper[ID]): Int = {
    ord.compare(key, that.key)
  }

  def setKey(key: ID): this.type = {
    this.key = key
    this
  }
}

/**
 * [[SortDataFormat]] of [[UncompressedInBlock]] used by [[Sorter]].
 */
private class UncompressedInBlockSort[@specialized(Int, Long) ID: ClassTag](
    implicit ord: Ordering[ID])
  extends SortDataFormat[KeyWrapper[ID], UncompressedInBlock[ID]] {

  override def newKey(): KeyWrapper[ID] = new KeyWrapper()

  override def getKey(
      data: UncompressedInBlock[ID],
      pos: Int,
      reuse: KeyWrapper[ID]): KeyWrapper[ID] = {
    if (reuse == null) {
      new KeyWrapper().setKey(data.srcIds(pos))
    } else {
      reuse.setKey(data.srcIds(pos))
    }
  }

  override def getKey(
      data: UncompressedInBlock[ID],
      pos: Int): KeyWrapper[ID] = {
    getKey(data, pos, null)
  }

  private def swapElements[@specialized(Int, Float) T](
      data: Array[T],
      pos0: Int,
      pos1: Int): Unit = {
    val tmp = data(pos0)
    data(pos0) = data(pos1)
    data(pos1) = tmp
  }

  override def swap(data: UncompressedInBlock[ID], pos0: Int, pos1: Int): Unit = {
    swapElements(data.srcIds, pos0, pos1)
    swapElements(data.dstEncodedIndices, pos0, pos1)
    swapElements(data.ratings, pos0, pos1)
  }

  override def copyRange(
      src: UncompressedInBlock[ID],
      srcPos: Int,
      dst: UncompressedInBlock[ID],
      dstPos: Int,
      length: Int): Unit = {
    System.arraycopy(src.srcIds, srcPos, dst.srcIds, dstPos, length)
    System.arraycopy(src.dstEncodedIndices, srcPos, dst.dstEncodedIndices, dstPos, length)
    System.arraycopy(src.ratings, srcPos, dst.ratings, dstPos, length)
  }

  override def allocate(length: Int): UncompressedInBlock[ID] = {
    new UncompressedInBlock(
      new Array[ID](length), new Array[Int](length), new Array[Float](length))
  }

  override def copyElement(
      src: UncompressedInBlock[ID],
      srcPos: Int,
      dst: UncompressedInBlock[ID],
      dstPos: Int): Unit = {
    dst.srcIds(dstPos) = src.srcIds(srcPos)
    dst.dstEncodedIndices(dstPos) = src.dstEncodedIndices(srcPos)
    dst.ratings(dstPos) = src.ratings(srcPos)
  }
}

/**
 * Creates in-blocks and out-blocks from rating blocks.
 * @param prefix prefix for in/out-block names
 * @param ratingBlocks rating blocks
 * @param srcPart partitioner for src IDs
 * @param dstPart partitioner for dst IDs
 * @return (in-blocks, out-blocks)
 */
private def makeBlocks[ID: ClassTag](
    prefix: String,
    ratingBlocks: RDD[((Int, Int), RatingBlock[ID])],
```

Alternating Least Squares (spark.ml)

Apache SystemML™

```
  srcPart: Partitioner,
  dstPart: Partitioner,
  storageLevel: StorageLevel)(
  implicit srcOrd: Ordering[ID]): (RDD[(Int, InBlock[ID])], RDD[(Int, OutBlock)]) = {
val inBlocks = ratingBlocks.map {
  case ((srcBlockId, dstBlockId), RatingBlock(srcIds, dstIds, ratings)) =>
    // The implementation is a faster version of
    // val dstIdToLocalIndex = dstIds.toSet.toSeq.sorted.zipWithIndex.toMap
    val start = System.nanoTime()
    val dstIdSet = new OpenHashSet[ID](1 << 20)
    dstIds.foreach(dstIdSet.add)
    val sortedDstIds = new Array[ID](dstIdSet.size)
    var i = 0
    var pos = dstIdSet.nextPos(0)
    while (pos != -1) {
      sortedDstIds(i) = dstIdSet.getValue(pos)
      pos = dstIdSet.nextPos(pos + 1)
      i += 1
    }
    assert(i == dstIdSet.size)
    Sorting.quickSort(sortedDstIds)
    val dstIdToLocalIndex = new OpenHashMap[ID, Int](sortedDstIds.length)
    i = 0
    while (i < sortedDstIds.length) {
      dstIdToLocalIndex.update(sortedDstIds(i), i)
      i += 1
    }
    logDebug(
      "Converting to local indices took " + (System.nanoTime() - start) / 1e9 + " seco
    val dstLocalIndices = dstIds.map(dstIdToLocalIndex.apply)
    (srcBlockId, (dstBlockId, srcIds, dstLocalIndices, ratings))
}.groupByKey(new ALSPartitioner(srcPart.numPartitions))
  .mapValues { iter =>
    val builder =
      new UncompressedInBlockBuilder[ID](new LocalIndexEncoder(dstPart.numPartitions))
    iter.foreach { case (dstBlockId, srcIds, dstLocalIndices, ratings) =>
      builder.add(dstBlockId, srcIds, dstLocalIndices, ratings)
    }
    builder.build().compress()
  }.setName(prefix + "InBlocks")
  .persist(storageLevel)
val outBlocks = inBlocks.mapValues { case InBlock(srcIds, dstPtrs, dstEncodedIndices, _
  val encoder = new LocalIndexEncoder(dstPart.numPartitions)
  val activeIds = Array.fill(dstPart.numPartitions)(mutable.ArrayBuilder.make[Int])
  var i = 0
  val seen = new Array[Boolean](dstPart.numPartitions)
  while (i < srcIds.length) {
    var j = dstPtrs(i)
    ju.Arrays.fill(seen, false)
    while (j < dstPtrs(i + 1)) {
      val dstBlockId = encoder.blockId(dstEncodedIndices(j))
      if (!seen(dstBlockId)) {
        activeIds(dstBlockId) += i // add the local index in this out-block
        seen(dstBlockId) = true
      }
      j += 1
    }
    i += 1
  }
  activeIds.map { x =>
    x.result()
  }
}.setName(prefix + "OutBlocks")
  .persist(storageLevel)
(inBlocks, outBlocks)
}

/**
 * Compute dst factors by constructing and solving least square problems.
 *
 * @param srcFactorBlocks src factors
 * @param srcOutBlocks src out-blocks
 * @param dstInBlocks dst in-blocks
 * @param rank rank
 * @param regParam regularization constant
 * @param srcEncoder encoder for src local indices
 * @param implicitPrefs whether to use implicit preference
 * @param alpha the alpha constant in the implicit preference formulation
 * @param solver solver for least squares problems
 *
 * @return dst factors
 */
private def computeFactors[ID](
    srcFactorBlocks: RDD[(Int, FactorBlock)],
    srcOutBlocks: RDD[(Int, OutBlock)],
    dstInBlocks: RDD[(Int, InBlock[ID])],
    rank: Int,
    regParam: Double,
    srcEncoder: LocalIndexEncoder,
    implicitPrefs: Boolean = false,
    alpha: Double = 1.0,
    solver: LeastSquaresNESolver): RDD[(Int, FactorBlock)] = {
  val numSrcBlocks = srcFactorBlocks.partitions.length
  val YtY = if (implicitPrefs) Some(computeYtY(srcFactorBlocks, rank)) else None
  val srcOut = srcOutBlocks.join(srcFactorBlocks).flatMap {
    case (srcBlockId, (srcOutBlock, srcFactors)) =>
      srcOutBlock.view.zipWithIndex.map { case (activeIndices, dstBlockId) =>
        (dstBlockId, (srcBlockId, activeIndices.map(idx => srcFactors(idx))))
      }
  }
  val merged = srcOut.groupByKey(new ALSPartitioner(dstInBlocks.partitions.length))
  dstInBlocks.join(merged).mapValues {
    case (InBlock(dstIds, srcPtrs, srcEncodedIndices, ratings), srcFactors) =>
      val sortedSrcFactors = new Array[FactorBlock](numSrcBlocks)
      srcFactors.foreach { case (srcBlockId, factors) =>
        sortedSrcFactors(srcBlockId) = factors
      }
      val dstFactors = new Array[Array[Float]](dstIds.length)
      var j = 0
      val ls = new NormalEquation(rank)
      while (j < dstIds.length) {
        ls.reset()
        if (implicitPrefs) {
          ls.merge(YtY.get)
        }
        var i = srcPtrs(j)
        var numExplicits = 0
        while (i < srcPtrs(j + 1)) {
          val encoded = srcEncodedIndices(i)
          val blockId = srcEncoder.blockId(encoded)
          val localIndex = srcEncoder.localIndex(encoded)
          val srcFactor = sortedSrcFactors(blockId)(localIndex)
          val rating = ratings(i)
          if (implicitPrefs) {
            // Extension to the original paper to handle b < 0. confidence is a function of |b|
            // instead so that it is never negative. c1 is confidence - 1.0.
            val c1 = alpha * math.abs(rating)
            // For rating <= 0, the corresponding preference is 0. So the term below is only added
            // for rating > 0. Because YtY is already added, we need to adjust the scaling here.
            if (rating > 0) {
              numExplicits += 1
              ls.add(srcFactor, (c1 + 1.0) / c1, c1)
            }
          } else {
            ls.add(srcFactor, rating)
            numExplicits += 1
          }
          i += 1
        }
        // Weight lambda by the number of explicit ratings based on the ALS-WR paper.
        dstFactors(j) = solver.solve(ls, numExplicits * regParam)
        j += 1
      }
      dstFactors
  }
}

/**
 * Computes the Gramian matrix of user or item factors, which is only used in implicit preference.
 * Caching of the input factors is handled in [[ALS#train]].
 */
private def computeYtY(factorBlocks: RDD[(Int, FactorBlock)], rank: Int): NormalEquation = {
  factorBlocks.values.aggregate(new NormalEquation(rank))(
    seqOp = (ne, factors) => {
      factors.foreach(ne.add(_, 0.0))
      ne
    },
    combOp = (ne1, ne2) => ne1.merge(ne2))
}

/**
 * Encoder for storing (blockId, localIndex) into a single integer.
 *
 * We use the leading bits (including the sign bit) to store the block id and the rest to store
 * the local index. This is based on the assumption that users/items are approximately evenly
 * partitioned. With this assumption, we should be able to encode two billion distinct values.
 *
 * @param numBlocks number of blocks
 */
private[recommendation] class LocalIndexEncoder(numBlocks: Int) extends Serializable {
  require(numBlocks > 0, s"numBlocks must be positive but found $numBlocks.")

  private[this] final val numLocalIndexBits =
    math.min(java.lang.Integer.numberOfLeadingZeros(numBlocks - 1), 31)
  private[this] final val localIndexMask = (1 << numLocalIndexBits) - 1
```

```scala
  /** Encodes a (blockId, localIndex) into a single integer. */
  def encode(blockId: Int, localIndex: Int): Int = {
    require(blockId < numBlocks)
    require((localIndex & ~localIndexMask) == 0)
    (blockId << numLocalIndexBits) | localIndex
  }

  /** Gets the block id from an encoded index. */
  @inline
  def blockId(encoded: Int): Int = {
    encoded >>> numLocalIndexBits
  }

  /** Gets the local index from an encoded index. */
  @inline
  def localIndex(encoded: Int): Int = {
    encoded & localIndexMask
  }
}

/**
 * Partitioner used by ALS. We requires that getPartition is a projection. That is, for any key k,
 * we have getPartition(getPartition(k)) = getPartition(k). Since the the default HashPartitioner
 * satisfies this requirement, we simply use a type alias here.
 */
private[recommendation] type ALSPartitioner = org.apache.spark.HashPartitioner
```

25 lines' worth of algorithm…

…mixed with 800 lines of performance code

Alternating Least Squares (in R)

Apache SystemML™

```
U = rand(nrow(X), r, min = -1.0, max = 1.0);
V = rand(r, ncol(X), min = -1.0, max = 1.0);
while(i < mi) {
   i = i + 1; ii = 1;
   if (is_U)
      G = (W * (U %*% V - X)) %*% t(V) + lambda * U;
   else
      G = t(U) %*% (W * (U %*% V - X)) + lambda * V;
   norm_G2 = sum(G ^ 2); norm_R2 = norm_G2;
   R = -G; S = R;
   while(norm_R2 > 10E-9 * norm_G2 & ii <= mii) {
     if (is_U) {
       HS = (W * (S %*% V)) %*% t(V) + lambda * S;
       alpha = norm_R2 / sum (S * HS);
       U = U + alpha * S;
     } else {
       HS = t(U) %*% (W * (U %*% S)) + lambda * S;
       alpha = norm_R2 / sum (S * HS);
       V = V + alpha * S;
     }
     R = R - alpha * HS;
     old_norm_R2 = norm_R2; norm_R2 = sum(R ^ 2);
     S = R + (norm_R2 / old_norm_R2) * S;
     ii = ii + 1;
   }
   is_U = ! is_U;
}
```

Alternating Least Squares (in R)

(in SystemML's subset of R)

Apache SystemML™

```
U = rand(nrow(X), r, min = -1.0, max = 1.0);
V = rand(r, ncol(X), min = -1.0, max = 1.0);
while(i < mi) {
   i = i + 1; ii = 1;
   if (is_U)
      G = (W * (U %*% V - X)) %*% t(V) + lambda * U;
   else
      G = t(U) %*% (W * (U %*% V - X)) + lambda * V;
   norm_G2 = sum(G ^ 2); norm_R2 = norm_G2;
   R = -G; S = R;
   while(norm_R2 > 10E-9 * norm_G2 & ii <= mii) {
     if (is_U) {
       HS = (W * (S %*% V)) %*% t(V) + lambda * S;
       alpha = norm_R2 / sum (S * HS);
       U = U + alpha * S;
     } else {
       HS = t(U) %*% (W * (U %*% S)) + lambda * S;
       alpha = norm_R2 / sum (S * HS);
       V = V + alpha * S;
     }
     R = R - alpha * HS;
     old_norm_R2 = norm_R2; norm_R2 = sum(R ^ 2);
     S = R + (norm_R2 / old_norm_R2) * S;
     ii = ii + 1;
   }
   is_U = ! is_U;
}
```

SystemML can compile and run this algorithm at scale

No additional performance code needed!

How fast does it run?

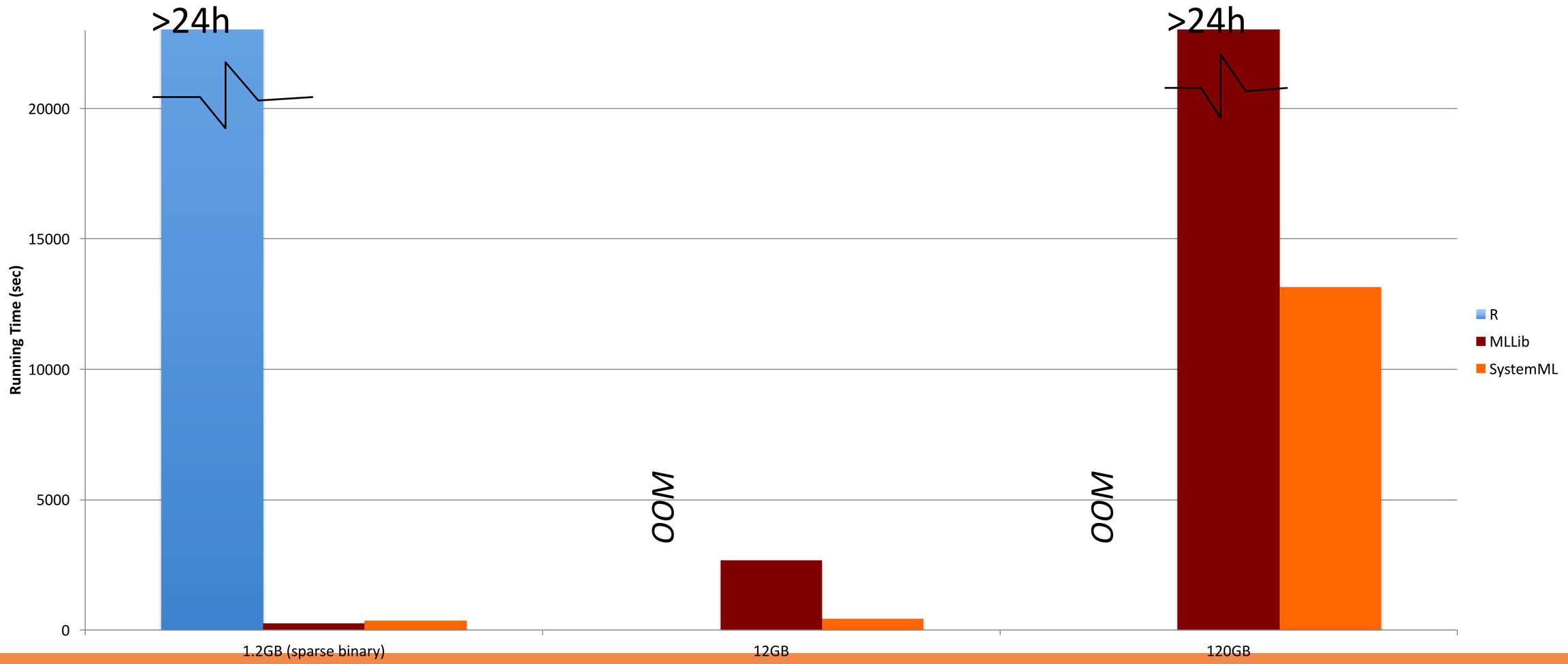
Apache SystemML™

Running time comparisons between machine learning algorithms are problematic

- Different, equally-valid answers
- Different convergence rates on different data

- But we'll do one anyway

Performance Comparison: ALS



Details:

Synthetic data, 0.01 sparsity, 10^5 products × {10^5,10^6,10^7} users. Data generated by multiplying two rank-50 matrices of normally-distributed data, sampling from the resulting product, then adding Gaussian noise. Cluster of 6 servers with 12 cores and 96GB of memory per server. Number of iterations tuned so that all algorithms produce comparable result quality.

Takeaway Points

Apache SystemML™

SystemML runs the R script in parallel

- Same answer as original R script
- Performance is comparable to a low-level RDD-based implementation

How does SystemML achieve this result?

The SystemML Runtime for Spark

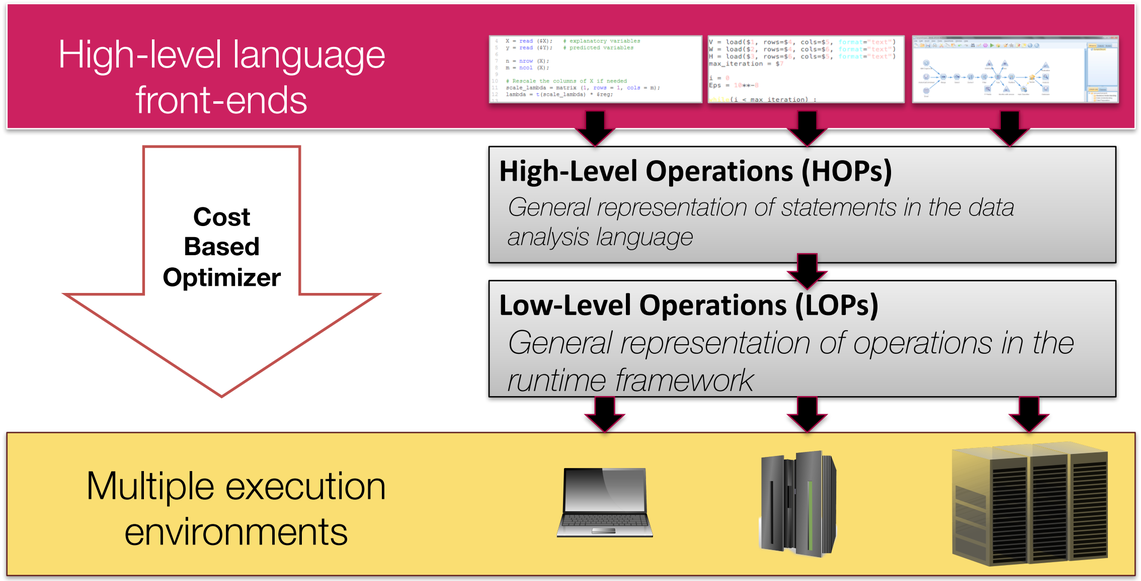
Apache SystemML™

Automates critical performance decisions

- *Distributed or local computation?*
- *How to partition the data?*
- *To persist or not to persist?*

Distributed vs local: Hybrid runtime

- Multithreaded computation in Spark Driver
- Distributed computation in Spark Executors
- Optimizer makes a cost-based choice



But wait, there's more!

Apache SystemML™

Many other rewrites

Cost-based selection of physical operators

Dynamic recompilation for accurate stats

Parallel FOR (ParFor) optimizer

Direct operations on RDD partitions

YARN and MapReduce support

Summary

Apache SystemML™

Cost-based compilation of machine learning algorithms generates execution plans

- for single-node in-memory, cluster, and hybrid execution
- for varying data characteristics:
  - varying number of observations (1,000s to 10s of billions), number of variables (10s to 10s of millions), dense and sparse data
- for varying cluster characteristics (memory configurations, degree of parallelism)

Out-of-the-box, scalable machine learning algorithms

- e.g. descriptive statistics, regression, clustering, and classification

"Roll-your-own" algorithms

- Enable programmer productivity (no worry about scalability, numeric stability, and optimizations)
- Fast turn-around for new algorithms

Higher-level language shields algorithm development investment from platform progression

- Yarn for resource negotiation and elasticity
- Spark for in-memory, iterative processing

Algorithms

Apache SystemML™

Category	Description	
Descriptive Statistics	Univariate	
	Bivariate	
	Stratified Bivariate	
Classification	Logistic Regression (multinomial)	
	Multi-Class SVM	
	Naïve Bayes (multinomial)	
	Decision Trees	
	Random Forest	
Clustering	k-Means	
Regression	Linear Regression	system of equations
		CG (conjugate gradient)
	Generalized Linear Models (GLM)	Distributions: Gaussian, Poisson, Gamma, Inverse Gaussian, Binomial, Bernoulli
		Links for all distributions: identity, log, sq. root, inverse, $1/\mu^2$
		Links for Binomial / Bernoulli: logit, probit, cloglog, cauchit
	Stepwise	Linear
		GLM
Dimension Reduction	PCA	
Matrix Factorization	ALS	direct solve
		CG (conjugate gradient descent)
Survival Models	Kaplan Meier Estimate	
	Cox Proportional Hazard Regression	
Predict	Algorithm-specific scoring	
Transformation (native)	Recoding, dummy coding, binning, scaling, missing value imputation	
PMML models	lm, kmeans, svm, glm, mlogit	

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Live Demo

Demo – Movie Recommendation

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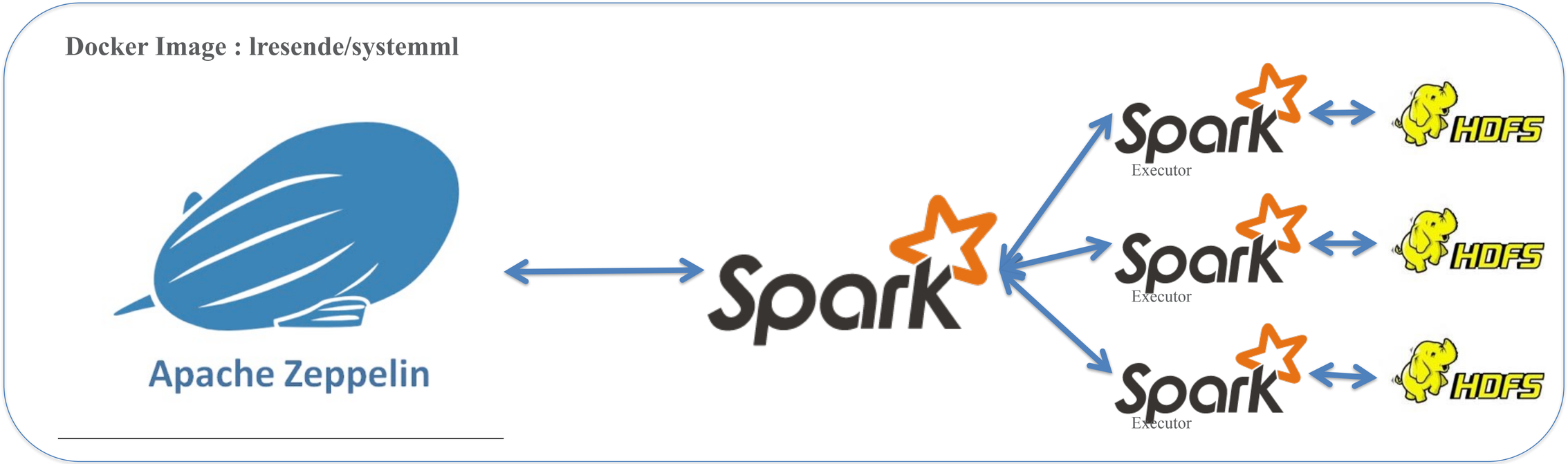
The demo environment

https://github.com/lresende/docker-systemml-notebook



Demo – Movie Recommendation

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The Netflix Data Set

- **Movies**

Movie	Year	Description
1	2003	Dinosaur Planet

- **Historical Ratings (training set)**

Movie	User	Rating	Date
1	30878	4	2005-12-26

Demo – Movie Recommendation

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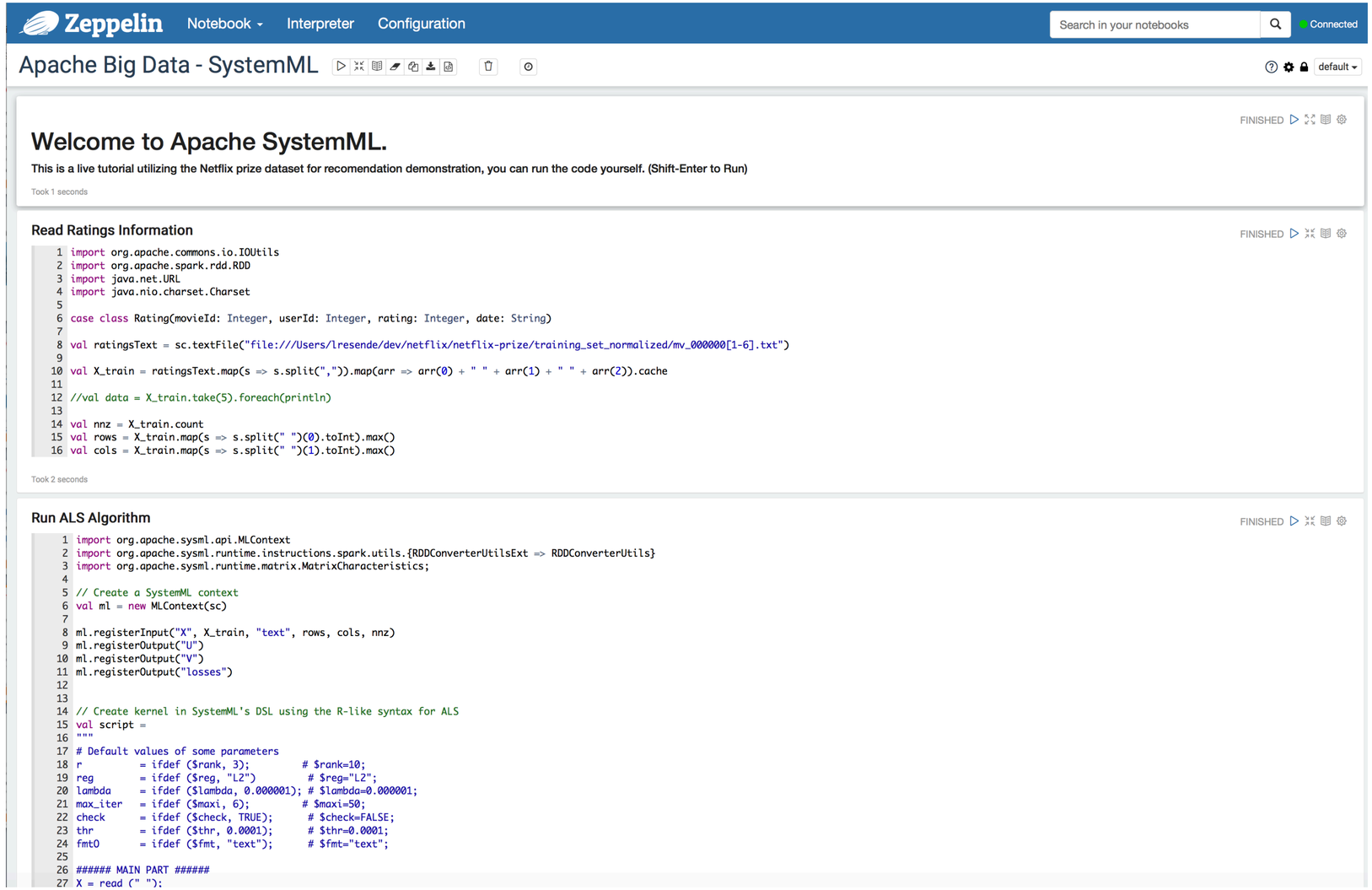

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What's new on SystemML

IBM | Spark Technology Center

VLDB 2016 Best Paper Award

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VLDB 2016 Best Paper and Demonstration

Read Compressed Linear Algebra for

Large-Scale Machine Learning.

http://www.vldb.org/pvldb/vol9/p960-elgohary.pdf

SystemML 0.11-incubating Release

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Features

- SystemML frames
- New MLContext API
- Transform functions based on SystemML frames
- Various bug fixes

Experimental Features / Algorithms

- New built-in functions for deep learning (convolution and pooling)
- Deep learning library (DML bodied functions)
- Python DSL Integration
- GPU Support
- Compressed Linear Algebra

SystemML 0.11-incubating Release

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New Algorithms

- Lasso
- kNN
- Lanczos
- PPCA

Deep Learning Algorithms

- CNN (Lenet)
- RBM

New SystemML Website

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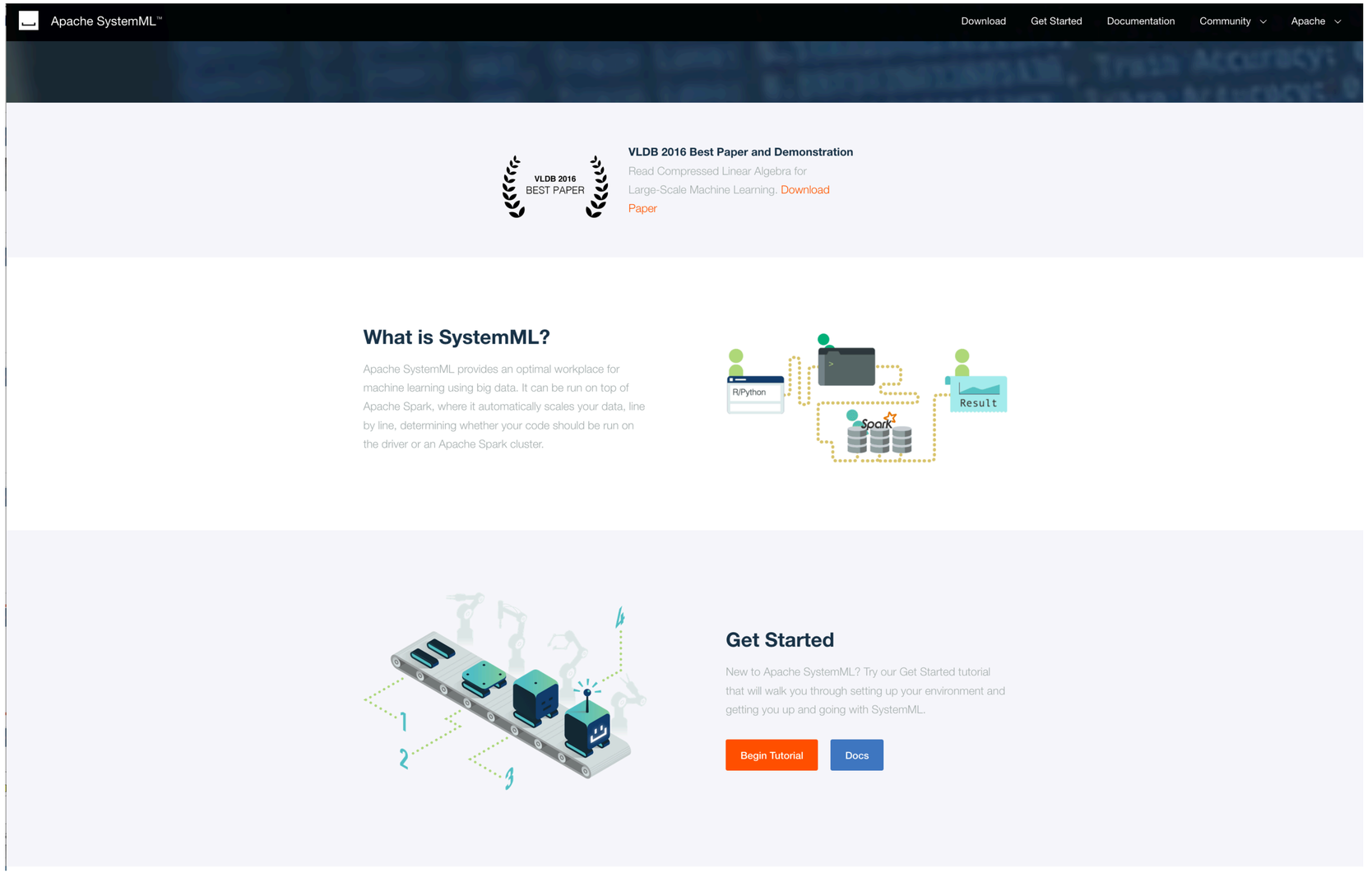

SystemML use cases

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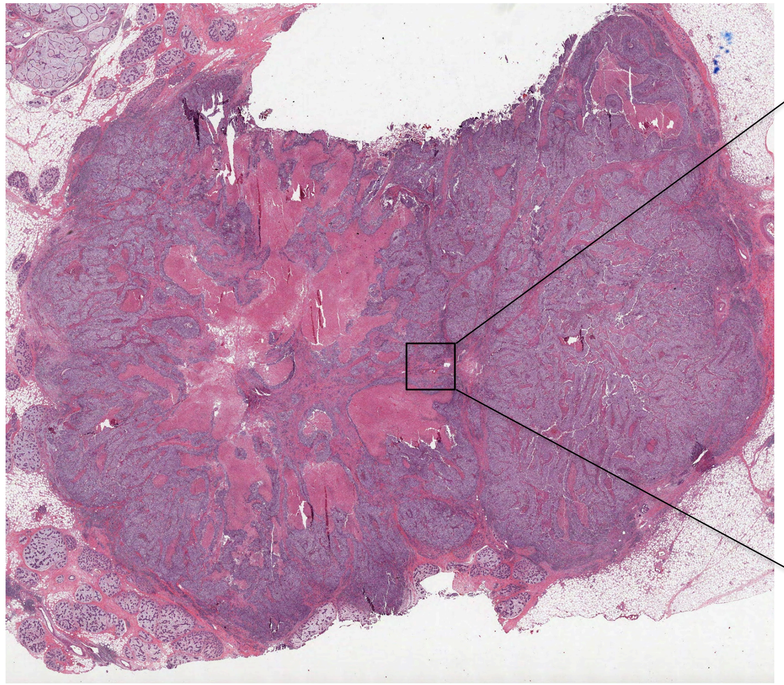
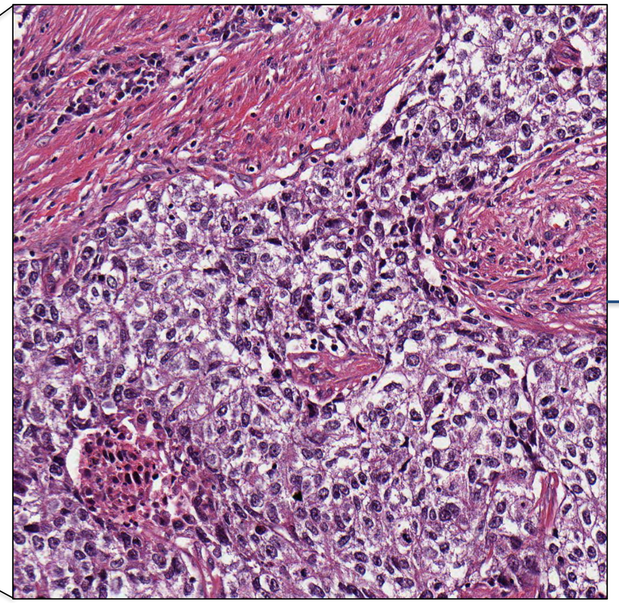
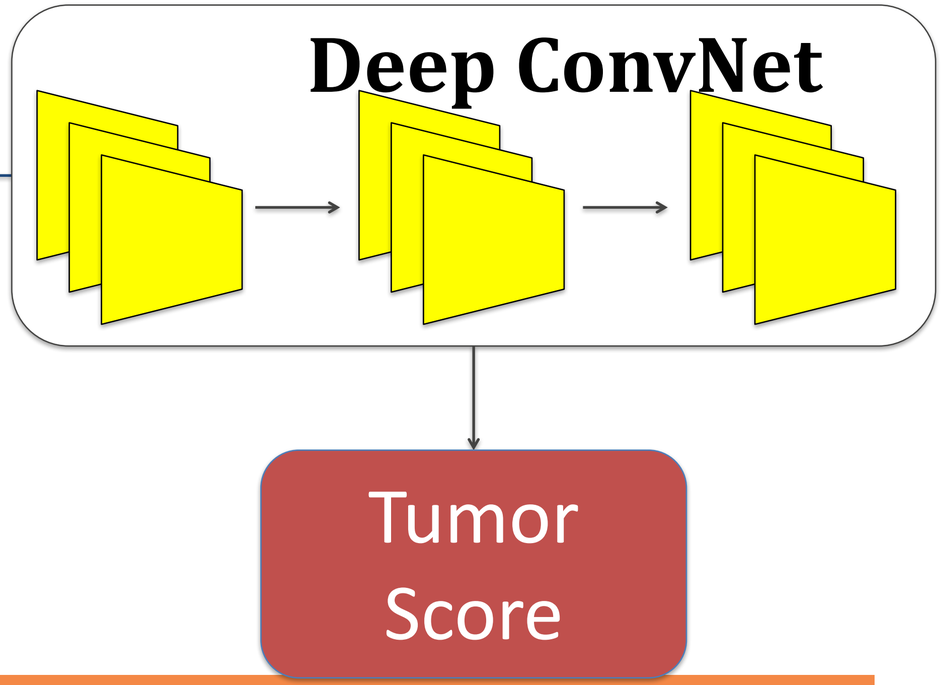
Using Deep Learning to assess Tumor proliferation by MIKE DUSENBERRY

Whole-Slide Image:



Sample Image:





Tumor Score

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Come contribute to SystemML

Apache SystemML

SystemML is open source!

- Announced in June 2015
- Available on Github since September 1
- First open-source binary release (0.8.0) in October 2015
- Entered Apache incubation in November 2015
- First Apache open-source binary release (0.9) available now
- Latest 0.11-incubating release just came out couple days ago

We are actively seeking contributors and users!

References

SystemML

http://systemml.apache.org

DML (R) Language Reference

https://apache.github.io/incubator-systemml/dml-language-reference.html

Algorithms Reference

http://systemml.apache.org/algorithms

Runtime Reference

https://apache.github.io/incubator-systemml/#running-systemml

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