ABSTRACT
This paper describes a workflow manager developed and deployed at Yahoo called Nova, which pushes continually-arriving data through graphs of Pig programs executing on Hadoop clusters. Nova is like data stream managers in its support for stateful incremental processing, but unlike them in that it deals with data in large batches using disk-based processing. Batched incremental processing is a good fit for a large fraction of Yahoo’s data processing use-cases, which deal with continually-arriving data and benefit from incremental algorithms, but do not require ultra-low-latency processing.

1. INTRODUCTION
Internet companies such as Yahoo, as well as many other kinds of organizations, continuously process large incoming data feeds to derive value from them. Examples at Yahoo include:

- Ingesting and analyzing user behavior logs (e.g. clicks, searches), to refine matching and ranking algorithms for search, content and advertising. Many steps are involved, including session inference, named entity recognition, and topic classification.
- Building and updating a search index from a stream of crawled web pages. Some of the numerous steps are de-duplication, link analysis for spam and quality classification, joining with click-based popularity measurements, and document inversion.
- Processing semi-structured data feeds, e.g. news and (micro-)blogs. Steps include de-duplication, geographic location resolution, and named entity recognition.

Processing along these lines is increasingly carried out on a new generation of flexible and scalable data management platforms, such as Pig/Hadoop [1, 4]. Hadoop is a scalable, fault-tolerant system for running individual map-reduce [10] processing operations over unstructured data files. Pig adds higher-level, structured abstractions for data and processing. In Pig, a language called Pig Latin [19] is used to describe arbitrary acyclic data flow graphs comprised of two kinds of operations: (1) built-in relational-algebra-style operations (e.g. filter, join); and (2) custom user-defined operations (e.g. extract web page hyperlinks, compute quantiles of a set of numbers).

Despite the success of Pig/Hadoop, it is becoming apparent that a new, higher, layer is needed: a workflow manager that deals with a graph of interconnected Pig Latin programs, with data passed between them in a continuous fashion. Given that Pig itself deals with graphs of interconnected data processing steps, it is natural to ask why one would layer another graph abstraction on top of Pig. It turns out that a “graph-of-graphs” programming model has several advantages:

- Modularity. The overall data processing workflow, which can be quite large (perhaps hundreds of steps), is broken into smaller modules. The modules (e.g. de-duplication, named entity recognition) may be programmed by different people/teams at different times, and can be re-used in other workflows.
- Independent scheduling. Modules may be scheduled at different times/rates. For example, global link analysis algorithms may only be run occasionally due to their costly nature and consumers’ tolerance for staleness. On the other hand, the pathway that ingests new news articles, tags them with (somewhat stale) link analysis scores, and folds them into an index for serving, needs to operate (almost) continuously.
- Cross-module optimization. Given the first two items, which provide flexibility in programming and scheduling of workflow components, it is desirable for an overarching workflow manager to identify and exploit certain optimization opportunities. For example, given two workflow components that consume a common input and wind up being scheduled around the same time, it can be beneficial to merge them dynamically to amortize the data reading cost. Other, more aggressive multi-query optimization strategies can be employed, as well as automatic pipelining: connecting the output of one module directly to the input of a subsequent module (subject to scheduling and fault-tolerance considerations), to avoid the overhead of materializing the intermediate result in