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Partitioning Strategies for Concurrent Programming

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Abstract

This work presents four partitioning strategies, or design patterns, useful for decomposing a serial application into multiple concurrently executing parts. These partitioning strategies augment the commonly used task and data parallel design patterns by recognizing that applications are spatiotemporal in nature. Therefore, data and instruction decomposition are further distinguished by whether the partitioning is done in the spatial or in temporal dimension. Thus, this work describes four decomposition strategies: spatial data partitioning (SDP), temporal data partitioning (TDP), spatial instruction partitioning (SIP), and temporal instruction partitioning (TIP), while cataloging the benefits and drawbacks of each. In addition, the practical use of these strategies is demonstrated through a case study in which they are applied to implement several different parallelizations of a multicore H.264 encoder for HD video. This case study illustrates both the application of the patterns and their effects on the performance of the encoder.

1 Introduction

Design patterns for parallel computing help to add structure and discipline to the process of concurrent software development [15, 16, 19, 13, 12, 20]. Two of the most commonly referenced parallel patterns are *task* and *data* parallelism. Using the task parallel pattern, a program is decomposed into concurrent units which execute separate instructions simultaneously. Using the data parallel pattern a program is decomposed into concurrent units which execute the same instructions on distinct data.

This work extends both the task and data parallel patterns by noting that applications execute in time and space. If one assigns spatial and temporal indices to a program's data and instructions, then it is possible to decompose both data and instructions in time and space. Thus, this work recognizes four partitioning strategies for exploiting concurrency in an application: spatial data partitioning (SDP), temporal data partitioning (TDP), spatial instruction partitioning (SIP), and temporal instruction partitioning (TIP).

Recognizing patterns that distinguish between temporal and spatial partitioning is important for the following reasons:

- This distinction provides an additional set of options for finding concurrency in an application.
- Recognizing the difference between spatial and temporal partitionings provides greater descriptive power for documenting and characterizing a parallel application.
- Perhaps most significantly, temporal and spatial partitioning affect the performance of an application in separate ways.

To understand the effect on performance, consider an application that continuously interacts with the outside world by processing a sequence of inputs and producing a sequence of outputs. Examples include desktop applications that interact with a human, embedded applications that interact with sensors, and system software that provides quality of service guarantees to other applications. These interactive programs typically have both *throughput* and *latency* requirements. The throughput requirement specifies the rate at which inputs are processed while the latency requirement specifies the speed with which an individual input must be processed. While both spatial and temporal partitioning patterns improve throughput, only spatial partitionings can improve latency.

To illustrate the use of these patterns, this paper presents a case study in which several different strategies are applied to create parallel implementations of an H.264 video encoder [24, 9] on a multicore architecture. The case study demonstrates how the additional options of temporal and spatial partitioning can aid programming. In addition, the effects of different strategies on the throughput and latency of the encoder are cataloged.

The rest of this paper is organized as follows. Section 2 defines terminology and presents an example application that is used to illustrate concepts. Section 3 presents the four partitioning strategies describing both spatial and temporal decomposition of data and instructions. Section 4 presents the case study illustrating the use of these patterns. Section 5 covers related work and Section 6 concludes the paper.

2 Basics and terminology

This section presents the context and terminology used to describe the partitioning strategies listed in Section 3. It begins by introducing an example application: an intelligent security camera. The security camera example is used to illustrate many of the concepts in the remainder of the paper. Next, the terminology used to describe spatial and temporal indexing of a program is presented. Finally, the section discusses a simple procedure used to prepare an application for decomposition using the spatiotemporal design patterns described in Section 3.

2.1 Example application: an intelligent security camera

An intelligent security camera processes a sequence of input images, or frames, from a camera (e.g. [14]). The camera compresses the frames for efficient storage and searches the frames to detect objects of interest. The compressed video is stored to disk while a human is alerted to the presence of any objects of interest. Both the data (frames) and the instructions (compression and search) of the camera have spatial and temporal dimensions.

The primary data object manipulated by the camera is the frame. The frame consists of pixels where each pixel is generated by a spatially distinct sensor. The position of a pixel in a frame represents a spatial index into the camera's data. Frames are produced at regular time intervals and processed in sequence. Each frame is assigned a unique identifier corresponding to the order in which it was produced. The sequence of frames represents a temporal index into the camera's data. The spatiotemporal dimensions of the security camera are illustrated in Figure 1.

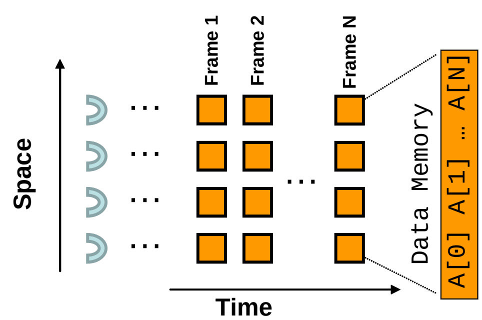


Figure 1. Spatiotemporal indexing of data in the security camera example. Spatially distributed sensors produce a sequence of pixels over time. The pixel's location in the frame is the spatial index while the frame number in the sequence in the temporal index.

The computation in the camera application consists of two primary functions: searching the frame for objects of interest and compressing the frames for storage. The compression operation is, in turn, made up of two distinct functions. First a series of image processing operations are executed to find and remove redundancy in the image stream, and, once the redundancy is eliminated, the remaining data is entropy encoded. Thus, there are three high-level functions which constitute the instructions of the camera: `search`, `eliminate`, and `encode`. As these functions occupy distinct regions of memory, their names can serve as spatial indices. To determine the temporal indices of these functions, note that the functions must be executed in a particular order to preserve correctness. The order of function execution represents an index into the temporal dimension of the camera's instructions. in this case `eliminate` must be executed before `encode`, but `search` is entirely independent. The spatiotemporal indexing of the camera's instructions is illustrated in Figure 2.

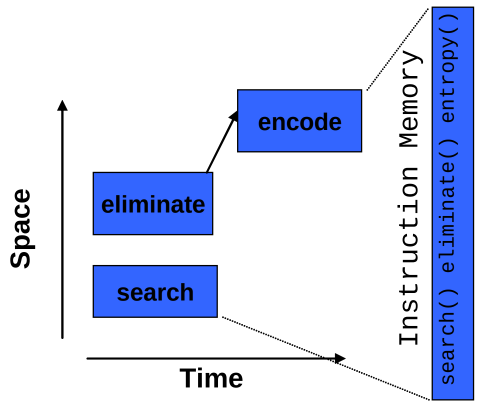


Figure 2. Spatiotemporal indexing of instructions in the security camera. Each frame produced by the camera is searched and encoded. The encoding process is further broken down into the eliminate redundancy and entropy encoding. The function name provides a spatial index. To define the temporal index, topological sort is performed on the dependence graph. The order of execution determined by the sort provides a temporal instruction index.

Note that the camera is typical of many interactive applications in that it has both latency and throughput requirements. The camera's throughput must keep up with the rate at which the sensor can produce frames. In addition, the camera must report objects of interest to the user with a low latency so that timely action can be taken.

2.2 Terminology

In this paper, the term *program* or *application* is used to refer to the problem to be decomposed into concurrent parts. A *process* is the basic unit of program execution, and a parallel program is one that has multiple processes actively performing computation at one time. A parallel program is created by *partitioning* or *decomposing* a program into multiple processes. A partitioning strategy represents a common pattern for performing this decomposition.

Programs operate by executing *instructions* to manipulate *data*. Both the data and instructions of a program have spatial and temporal components of execution. In order to partition a program, one must first define the spatial and temporal dimensions of the program's execution.

2.3 Preparing to partition a program

The following procedure determines the dimensionality of a program's instructions and data to prepare it for partitioning:

1. Determine what constitutes a single input to define the temporal dimension of the program's data. For some programs an input might be a single reading from a sensor. In other cases an input might be a file, data from a keyboard or a value internally generated by the program.

2. Determine the distinct components of an input to define the spatial dimension of the program's data.

3. Determine the distinct functions required to process an input to define the spatial dimension of the program's instructions.

4. Determine the partial ordering of functions using topological sort to define the temporal dimension of the program's instructions.

To illustrate the process, it is applied to the security camera example:

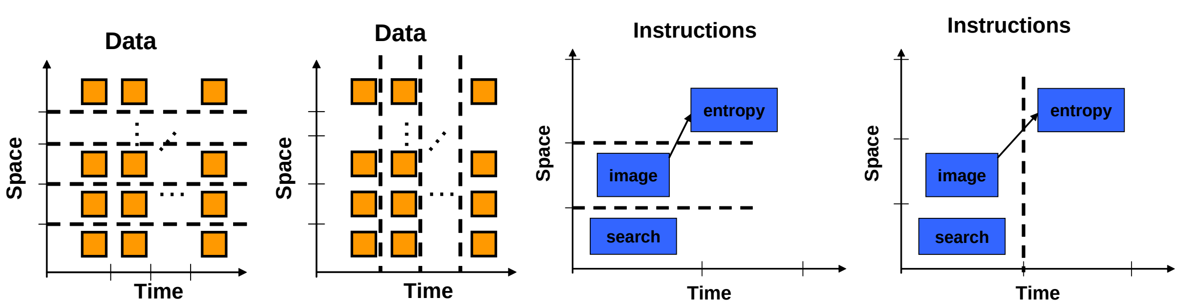
1. A single frame is an input, so the sequence of frames represents the temporal dimension of the camera data.
2. A frame is composed of individual pixels arranged in a two-dimensional array. The coordinates of pixels in the array represent the spatial dimension of the camera data.
3. The three major functions in the camera are: `search`, `eliminate`, and `encode`. These functions define the spatial dimension of the camera's instructions.
4. For a given frame, there is a dependence between the `eliminate` and `encode` functions while the `search` function is independent. These dependences determine the temporal dimension of the camera's instructions.

Applying this procedure defines the dimensionality of a program's data and instructions. Once this dimensionality is defined, it is possible to explore different spatiotemporal partitioning strategies.

3 A taxonomy of spatiotemporal partitioning strategies

The procedure described in Section 2.3 defines the spatial and temporal dimensionality of a program's instructions and data. Given this definition it is possible to apply one of the following four partitioning strategies: spatial data partitioning, temporal data partitioning, spatial instruction partitioning, and temporal instruction partitioning. This section presents the following for each of the four strategies:

- A brief description of the strategy.
- The context in which the strategy should be applied.
- The forces that influence the application of the strategy.
- An example showing how to apply the strategy to the security camera.
- Other example uses of the strategy.
- Related strategy patterns.



(a) **SDP** (b) **TDP** (c) **SIP** (d) **TIP**

Figure 3. Parallelization strategies.

3.1 Spatial data partitioning (SDP)

Description. Using the spatial data partitioning (SDP) strategy, data is divided among processes according to spatial index. Following this pattern, processes perform computation on spatially distinct data with the same temporal index. Typically, each process will perform all instructions on its assigned data. Additional instructions are usually added to SDP programs to enable communication and synchronization. This partitioning strategy is illustrated in Figure 3(a).

Context. SDP generally increases throughput and decreases latency, so it is useful when a single processor cannot meet either of these requirements for a given application. The performance of an SDP application will be best if the spatial data dimension is large and has few dependences.

Forces. The driving force behind the use of the SDP strategy is the improvement of both throughput and latency for the partitioned application. However, when applying this strategy one must consider the opposing forces of communication and load-balancing.

Communication can oppose the performance gains of the SDP strategy if the time spent transferring data is large enough to negate the performance benefit of parallelization. Unfortunately, communication in an SDP implementation is always application specific and, thus, there are no general guidelines for analyzing communication using this strategy. However, if a particular application is found to require a performance limiting amount of communication, spatial instruction partitioning may be considered, as SIP can also improve throughput and latency.

Load-balancing is another force limiting the potential performance gains of SDP. Since each process is responsible for executing all instructions on its assigned data the load-balance of an SDP application is determined by the relationship between the instructions and data. If the same instructions are executed regardless of the value of data, then an SDP implementation will be easy to load-balance. If the instructions executed are conditional on the value of data then an SDP implementation may be very difficult to load-balance as some data may cause one process to do more work than others. This difficulty can offset some of the performance gains of an SDP implementation. Implementation strategy patterns like the task-queue, or work-queue, and the master-worker pattern can help address load-imbalance [12].

Example in security camera. To implement the SDP strategy in the security camera example, separate processes work simultaneously on pixels from the same frame. Each process is responsible for executing the `search`, `eliminate`, and `encode` functions on its assigned pixels. Processes communicate with other processes responsible for neighboring spatial indices.

Other examples of SDP. This pattern is common in many parallel linear algebra implementations like ScaLAPACK [1] and PLAPACK [23]. The high performance Fortran language is designed to express and manipulate SDP at a high-level [6]. Single-instruction, multiple-data (SIMD) architectures are designed to exploit SDP [4]

Related Strategy Patterns. The DataDecomposition [16] and Data Parallelism [12] patterns are both used to take a data-centric approach to partitioning an application into concurrent units. In order to perform this decomposition an index set is defined over the program's data. The spatial data partitioning strategy is a sub-strategy of DataDecomposition and Data Parallelism in which the index set is restricted to spatial indices.

The TaskDecomposition and Task Parallelism patterns both take a task-centric approach to application decomposition. These patterns allow individual tasks to be composed of the same set of instructions. The case where each task is the same function applied to different spatial indices is equivalent to the SDP strategy.

3.2 Temporal data partitioning (TDP)

Description. Using the temporal data partitioning (TDP) strategy, data are divided among processes according to temporal index. Following this pattern, each process performs computation on all spatial indices associated with its assigned temporal index as illustrated in Figure 3(b). In a typical TDP implementation each process executes all instructions on the data from its assigned temporal index. Often, communication and synchronization instructions need to be added to allow processes to handle temporal data dependences.

Context. TDP can increase throughput but will not decrease latency. Thus, this strategy is useful when a single processor can meet the application's latency requirement, but not the throughput requirement. The performance of a TDP application will be best when the temporal dimension is large and has few dependences.

Forces. The driving force behind the use of the TDP pattern in the improvement in throughput. Opposing this force is the possible overhead of communication and load-balancing.

Communication overhead can counter the throughput gains of applying the TDP strategy. In addition, it is possible that the added communication can increase the application's latency compared to a single processor implementation. Communication in this pattern occurs when data produced at one temporal index is needed to process data at another temporal index. If the amount of communication required is found to limit performance, any of the other three spatiotemporal partitioning strategies can be tried as they all improve throughput.

Load-balancing in a TDP application tends to be easy. If the same work is done for each temporal data index then achieving good load-balance is trivial. If the computational load varies per temporal data index it can be more difficult to achieve an efficient load-balance; however, the TDP strategy naturally lends itself to implementation through patterns such as the work-queue and master-worker that can be used to address a load-imbalance.

Example in security camera. To implement TDP in the security camera example, each frame is assigned to a separate process and multiple frames are encoded simultaneously. A process is responsible for executing the `eliminate`, `encode`, and `search` functions on its assigned frame. Processes receive data from processes working on earlier temporal indices and send data to processes working on later temporal indices.

Other examples of TDP. Packet processing applications like SNORT are commonly parallelized using the TDP pattern [8]. This application processes a sequence of packets from a network, possibly searching them for viruses. As packets arrive they are assigned to a process which performs the required computation on that packet.

Related Strategy Patterns. The DataDecomposition [16] and Data Parallelism [12] patterns are both used to take a data-centric approach to partitioning an application into concurrent units. In order to perform this decomposition an index set is defined over the program's data. The temporal data partitioning strategy is a sub-strategy of DataDecomposition and Data Parallelism in which the index set is restricted to temporal indices.

Using the Pipeline strategy pattern, an application is partitioned into stages and data flows from one stage to the next [12]. If each stage is assigned the same instructions and processes data from different temporal indices concurrently then this instance of the pipeline strategy is equivalent to TDP.

The TaskDecomposition [16] and Task Parallelism [12] patterns both take a task-centric approach to partitioning an application. These patterns do not necessarily require that the tasks represent distinct functions or instructions. The specific case where each task represents the same set of functions applied to distinct temporal data indices is equivalent to TDP.

3.3 Spatial instruction partitioning (SIP)

Description. Using the spatial instruction partitioning (SIP) strategy, instructions are divided among processes according to spatial index. Following this pattern, each process performs a distinct computation using the same data. Often no communication is needed between processes. This strategy is illustrated in Figure 3(c).

Context. The SIP strategy can increase application throughput and decrease latency, so it is useful when a single processor cannot meet the application's throughput or latency requirements. In addition, the SIP strategy divides and application into several separate functional modules. Splitting a large, complicated application into several simpler pieces aids modular design and allows multiple engineers to work on an application independently. Furthermore, splitting the instructions of the application may simplify data dependences as the single set of dependences for the entire application is divided into several smaller sets of dependences for each module.

Forces. The performance gain and increase in modularity offered by the SIP strategy is opposed by the forces of communication overhead and load-balance.

Communication in SIP implementations is generally rare, given the definition of the temporal and spatial dimensions of instructions. Communication in SIP applications typically involves making the same data available to all processes. In some instances processes might need to communicate while executing their assigned instructions. In both cases it is important to ensure that the cost of communication does not negate any performance gains from applying SIP. If communication is found to limit performance, then spatial data partitioning should be investigated as it can also increase throughput while decreasing latency.

Load-balance is often an issue in SIP applications. Instructions are assigned to processes based because they represent logically coherent units. Unfortunately it is rare that these units represent the same amount of computation and, thus, it is often the case that one process is assigned more work than another. The work-queue and master-worker patterns can be used to implement the SIP strategy and help address load-balance, but their applicability can be limited by the amount of parallelism that exists in the spatial instruction dimension.

Example in the security camera. To implement SIP in the security camera, the `eliminate` and `encode` functions are coalesced into one `compress` function. This function is assigned to one process while the `search` function is assigned to a separate process. These two processes work on the same input frame at the same time. In this example, the two processes need not communicate. However, one can envision a camera that alters the quality of the compressed video based on the presence of an object of interest. In this scenario, the `search` function sends messages to the `compress` function to indicate when the quality should change.

Other examples of SIP. This pattern is sometimes used in image processing applications when two filters are applied to the same input image to extract different sets of features. In such an application each of the two filters represents a separate function and therefore a separate spatial instruction index. This application can be parallelized according the SIP strategy by assigning each filter to a separate process. Compilers that exploit instruction level parallelism often make use of this pattern as Butts and Sohi found that $35\,\%$ of dynamically created values are used multiple times. Some speculative execution systems, use SIP partitioning to execute multiple paths through a series of conditional instructions [22]. Additionally, this is strategy is the basis of multiple-instruction single-data (MISD) architectures [4].

Related Strategy Patterns. The TaskDecomposition [16] and Task Parallelism [12] patterns both take a task-centric view of an application. The SIP strategy corresponds to instances of these patterns where the tasks represent distinct functions and all tasks can execute concurrently.

3.4 Temporal instruction partitioning (TIP)

Description. Using the temporal instruction partitioning (TIP) strategy, instructions are divided among processes according to temporal index as illustrated in Figure 3(d). In a TIP application each process executes a distinct function and data flows from one process to another as defined by the dependence graph. This flow of data means that TIP applications always require communication instructions so that the output of one process can be used as input to another process. To achieve performance, this pattern relies on a long sequence of input data and each process executes a function on data that is associated with a different input or temporal data index.

Context. The TIP strategy can increase throughput but does not improve latency. Therefore, this strategy is most useful when a single processor cannot meet the application's throughput requirement, but can meet the latency requirement. Like the SIP strategy, TIP can also be useful for splitting a large application into smaller functional modules, which can simplify application development and separate a complicated set of data dependences into smaller units that are each individually easier to handle.

Forces. Countering the driving forces of throughput increase and increased modularity are the opposing forces of increased communication and inefficient load-balance.

The TIP strategy is guaranteed to require communication because the temporal instruction indices are defined according to their dependences. Therefore, every process in a TIP application can be expected to communicate with at least one other process. In addition to negating a throughput gain, this communication will also increase latency unless it is completely overlapped with computation. If the communication in a TIP application proves too deleterious to performance, any of the other three strategies can be explored as they all increase throughput. The SIP strategy is a useful alternative for modularity.

Load-balancing in TIP applications is often difficult. As with SIP applications, it is rare that the functions represented by different temporal instruction indices require the same computation. Thus, some processes may be assigned more work than others. Again, both the work-queue and master-worker patterns may be used to implement TIP and address the load-balancing issue; however, in practice these patterns are often conceptually difficult to reconcile with the TIP strategy.

Example in the security camera. To implement TIP in the security camera, the `eliminate` function is assigned to one process while the `encode` function is assigned to another. The `search` function can be assigned to a third process or it can be coalesced with one of the other functions to help with load balancing. In this implementation, one process executes the `eliminate` function for frame N while a second process executes the `encode` function for frame $N-1$.

Other examples of TIP. This pattern is often used to implement digital signal processing applications as they are easily expressed as a chain of dependent functions. In addition, this pattern forms the basis of streaming languages like StreamIt [5] and Brook [2]. The Pipeline construct in Intel's Threading Building Blocks also exploits the TIP strategy [7].

Related Parallel Patterns. The TaskDecomposition [16] and Task Parallelism [12] patterns both take a task-centric view of an application. The TIP strategy corresponds to instances of these patterns where the tasks are distinct functions connected through a chain of dependences. Similarly, the TIP pattern is equivalent to the Pipeline strategy pattern if all stages of the pipeline represent distinct functions.

3.5 Combining multiple strategies in a single program

It can often be helpful to combine partitioning strategies within an application to provide the benefit of multiple strategies, or to provide an increased degree of parallelism. The application of multiple strategies is viewed as a sequence of choices. The first choice creates multiple processes and these processes can then be further partitioned as if they were serial applications themselves.

Combining multiple choices in sequence allows the development of arbitrarily complex parallel programs and the security camera example demonstrates the benefits of combining multiple strategies. As illustrated above it is possible to use SIP partitioning to split the camera application into two processes. One process is responsible for the `search` function while another is responsible for the `eliminate` and `encode` functions. This SIP partitioning is useful because the searching computation and the compression computation have very different dependences and splitting them creates two simpler modules. Each of these simple modules is easier to understand and parallelize. While this partitioning improves throughput and latency, it suffers from a load-imbalance, because the searching and compressing functions do not have the same computational demand.

To address the load-imbalance and latency issues, one may apply a further partitioning strategy. For example, applying the SDP strategy to the process executing the compression will split that computationally intensive function into smaller parts. This additional partitioning helps to improve load-balance and application latency. (For a more detailed discussion of using SIP and SDP together in the camera, see [14].)

The case study presented in Section 4 includes other examples using multiple strategies to partition an application.

4 Case study

This section presents a case study using the partitioning strategies presented in Section 3 to create multicore implementations of an H.264 encoder for HD video. This study shows how the use of different strategies can affect both the development and performance of the parallelized application.

To begin, an overview of H.264 encoding covers the aspects of the application relevant to the partitioning. Next the hardware and software used in the study is briefly described. Then various partitioning strategies are described and the performance of each is presented.

First, the TDP strategy is used and is found to increase throughput, but to be detrimental to latency. Next SDP partitioning is used and demonstrates both throughput and latency improvements but requires some application specific sacrifice. TIP partitioning helps to simplify the design by decomposing a complicated set of dependences into simpler modules, but this simplification comes with a performance loss. Next a combination of TIP and SDP is found to provide a compromise between latency, throughput, and application specific concerns. Finally, the combination of TDP, TIP, and SDP is found to provide the maximum flexibility and allow the developer to tune latency and throughput requirements as desired.

4.1 H.264 overview

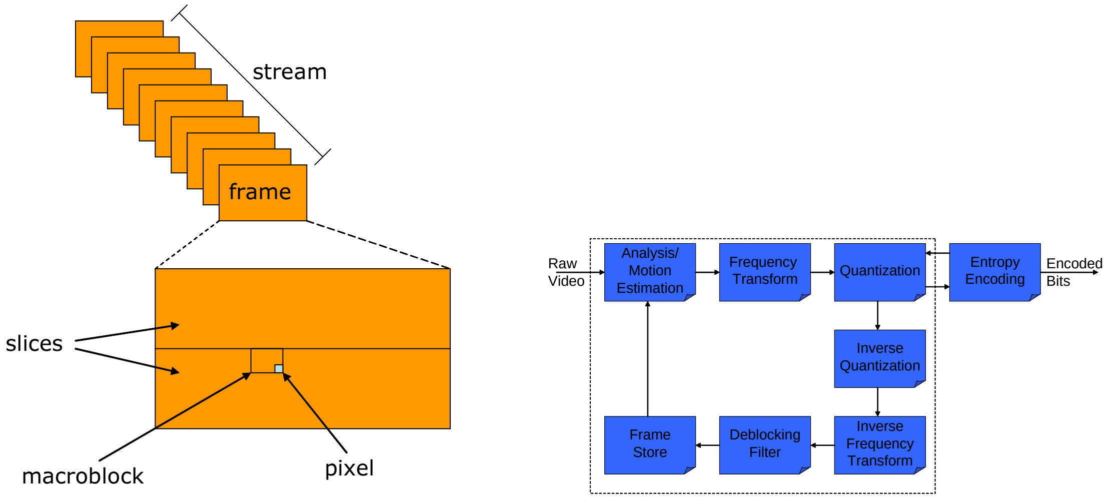
This section presents a brief overview of the aspects of H.264 encoding relevant to understanding the parallelization of the application. For a complete description of H.264 see [9, 24, 17].

H.264 is a standard for video compression. In fact, the H.264 standard could be used to implement the video compression discussed in the security camera example. The video consists of a stream of frames. H.264 each frame consists of one or more *slices*. A slice consists of *macroblocks* which are 16×16 regions of pixels. These concepts are illustrated in Figure 4(a).

An H.264 encoder compresses video by finding temporal and spatial redundancy in a video stream. Temporal redundancy refers to similarities that persist from frame to frame, while spatial redundancy refers to similarities within the same frame. Once this redundancy is found and eliminated, the encoder may remove some additional information which is often unnoticeable to the human eye. (This loss of information is why H.264 is described as a ”lossy” encoder.) Finally, the encoder performs entropy encoding on the transformed data for further compression.

Figure 4(b) shows the block diagram representing H.264 processing. The functions shown in the block diagram are used to process every macroblock in a frame. The analysis and motion estimation block is used to find temporal redundancy by searching for a similar region in a previously encoded frame and determining the best encoding modes for the macroblock. The frequency transform function is used to find temporal redundancy. Quantization removes low-frequency data to which the human eye is less sensitive. The inverse quantization and inverse transform blocks are used to reconstruct the frame as the decoder will see it. The deblocking filter removes artifacts inserted by the frequency transform. Finally, the frame store saves the reconstructed frame to serve as a reference for subsequently encoded frames. These functions represent the image processing portion of the encoding application and are analogous to the `eliminate` function in the security encoder example.

The remaining block in the diagram performs entropy encoding on the transformed data. H.264 supports two separate entropy encoding modes: CAVLC and CABAC. CAVLC stands for context adaptive variable length coding, while



(a) **H.264 Data** (b) **H.264 Instructions**

Figure 4. Data and instructions for H.264.

CABAC stands for context adaptive binary arithmetic coding. CABAC encoding is more computationally intensive but results in greater compression.

During the image processing phase, H.264 observes the following data dependences. Frames are dependent on reference frames (except for specially designated frames which are encoded without a reference and allow the process to begin). Slices are completely independent as defined by the standard, but this independence comes at the cost of reduced ability to find spatial redundancy. Within a slice, there is a dependence between macroblocks. A macroblock depends on four neighboring macroblocks: above and to the left, above, above and to the right, and to the left. This dependence among macroblocks in a slice is illustrated in Figure 5.

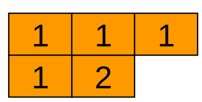


Figure 5. Macroblock dependence in image processing section of H.264. A macroblock is dependent on neighboring macroblocks above-left, above, above-right, and to the left. All macroblocks labeled “1” must be processed before the macroblock labeled “2.”

During the entropy encoding phase each, H.264 observes the following dependences. The entropy encoding of a frame is dependent on previous frames, but this can be relaxed for a small overhead in the encoded bitstream. The entropy encoding of slices is independent, but this independence also adds extra bits to the encoding. Within a slice, macroblocks must be written to the output in raster order. Thus, the entropy phase as defined here is serial within a slice.

Having described the salient features of H.264, the experimental methodology used to evaluate the partitioning strategies is discussed.

4.2 Experimental methodology

This section discusses the software and hardware used in the case study.

The open source x264 software code base is used as a basis for encoder development [25]. x264 is implemented in C with assembly to take advantage of SIMD instructions and hardware specific features. x264 is currently parallelized using the pthreads library[1] to implement the TDP strategy, while earlier versions of the encoder implemented a limited

[1] Although the case study uses the pthreads library, the term process will continue to be used to describe units of program execution.

form of the SDP strategy (which is no longer supported)[2]. x264 is highly configurable via the command line. For this study x264 is configured with a computationally aggressive parameter set to enable H.264 Main profile encoding of 1080p high-definition video[3].

All partitionings of the x264 code base are tested on an Intel x86 system. This system consists of four 2.4 GHz quad-core x86 processors communicating through shared memory. For this study, the hardware platform is treated as a sixteen-core multicore.

Each of the partitionings is implemented by modifying the x264 code and running the partitioned version on 2, 4, 8, and 16 cores with the number of processes equal to the number of cores. For each implementation and process count, the throughput (in frames/second) and latency (in milliseconds) are measured. In addition, as discussed above, some features of H.264 allow programmers to relax data dependences at the cost of lost quality and decreased compression. For this reason, the quality of each partitioning is also measured by recording the peak signal to noise ratio (PSNR measured in decibels) and the achieved compression in terms of output bitrate (measured in kilobits/second). For reference Table 1 shows these measurements for a single processor.

	Single Threaded x264
Throughput (frames/s)	1.24
Average frame latency (ms)	642
Image Quality (Average PSNR)	39.654
Encoded Bitrate (Kb/s)	11167.78

Table 1. Performance of single-threaded x264.

To prepare x264 for partitioning the procedure described in Section 2.3 is applied:

1. An input is a frame and the sequence of frames represents the temporal data index.
2. Each frame is optionally made up of slices and these slices are composed of macroblocks. Both the slice and the macroblock represent spatial data indices.
3. The image processing functions (implemented in x264 as `x264_macroblock_analyse` and `x264_macroblock_encode`) and the entropy encoding functions (implemented in x264 as x264_cavlc_write and the x264_cabac family of functions) represent the spatial instruction indices.
4. The dependence between the image processing and entropy encoding functions represents the temporal data index.

At this point, x264 is prepared to be partitioned.

4.3 H.264 with TDP

The first strategy studied is temporal data partitioning. As in the security camera, this strategy is implemented by assigning frames, or temporal data indices, to processes. Each process is responsible for executing the image processing and entropy encoding instructions on all pixels, or spatial data indices, of its assigned frames and the processes work on separate frames concurrently. (As noted above, this form of parallelism is supported in the x264 distribution.)

As described above, frames encoded later in the sequence use previously encoded frames for reference and may themselves be used as reference frames for subsequently encoded frames. Thus, a process is both a consumer and producer of reference frames. For the parameters used in this case study, a process may use up to five reference frames. To increase parallelism, processes make rows of reference frame pixels available as they are produced. This scheme comes at a cost of reducing the parallelized encoder's ability to find temporal redundancy in some video streams.

[2] The TDP implementation of the case study uses x264 as is. The SDP implementation recreated the earlier version of x264 in the current code base. The other three partitionings in the study represent original work.

[3] Specifically, x264 is invoked with the following command line parameters: `--qp 25 --partitions all --bframes 3 --ref 5 --direct auto --b-pyramid --weightb --bime --mixed-refs --no-fast-pskip --me umh --subme 5`. The input video is a 1080p sequence of a tractor plowing a field.

Load-balancing the parallel encoder using this strategy is fairly easy. Processes are only assigned new frames after completing previously assigned work. This way, a process which is assigned a particularly difficult frame can work on it without becoming a bottleneck. Even if the slow process is producing reference frame data, the fact that the encoder is limited to five reference frames minimizes the impact of one slow frame in a system with sixteen processes.

Table 2 shows the performance of the serial implementation and the TDP encoder for 2, 4, 8, and 16 processes. As expected, the TDP strategy helps to improve throughput, which steadily increases with increasing numbers of processes. Unfortunately, the latency of encoding an individual frame actually gets worse. There is a constant amount of overhead to pay for the communication and synchronization associated with communicating the reference frames. The encoder quality remains the same for a very modest increase in output bitrate.

	Serial x264	TDP x264			
Processes	1	2	4	8	16
Throughput (frames/s)	1.24	2.06	4.07	7.93	14.03
Average frame latency (ms)	642	910	899	893	916
Image Quality (Average PSNR)	39.654	39.654	39.654	39.654	39.654
Encoded Bitrate (Kb/s)	11167.78	11167.74	11175.38	11179.15	11210.06

Table 2. Performance of parallel x264 decomposed with the TDP strategy.

The TDP strategy is excellent for improving throughput, and easy to load-balance; however, it actually increases the latency of encoding a single frame.

4.4 H.264 with SDP

In an attempt to decrease the latency of the encoder, spatial data partitioning is employed. Following this strategy, a frame is divided into multiple slices and each slice is assigned to a separate process. Each process executes the image processing and entropy encoding functions on its assigned slice, and all processes wait until the current frame is encoded before moving on to a new frame. Thus, processes encode separate portions of the same frame concurrently. (As mentioned above, previous distributions of x264 implemented this strategy; for the case study SDP is re-implemented in the current x264 code base.)

As described above, slices provide independence in both the image processing and entropy encoding functions. This independence is especially important during entropy encoding which requires all macroblocks to be processed in order. However, the independence comes at the cost of reduced ability to find temporal redundancy and a decrease in the compression of the entropy encoding process.

Although load-balancing SDP programs is generally easy, it is difficult in the case of the H.264 encoder. The time taken to decode a macroblock is data dependent making some macroblocks easier to encode than others. Generally, regions of the frame with high motion take longer to encoder than low-motion regions. Thus some slices may take longer than others and become a bottleneck.

Table 3 shows the performance of the serial implementation and the SDP encoder for 2, 4, 8, and 16 processes. As expected, both the latency and throughput of the SDP parallelized encoder improve compared to the serial version. Unlike the TDP encoder, however, the performance of the SDP encoder appears to be reaching an asymptote as 16 processes provide little added benefit over 8 processes. This knee in the performance curve is due to the load-imbalance described above. Additionally, the quality of the encoder decreases while the encoded bit rate increases as more processes are used. This is because each additional process requires splitting the frame into additional slices and each slice reduces quality and adds overhead to the output bitstream.

Part of the difficulty implementing the SDP encoder comes from the dependence requiring each macroblock within a slice to be written in raster order. Although the entropy encoding is a small fraction of the total compute time, this concern dominates the design of the SDP encoder.

4.5 H.264 with TIP

In order to separate the image processing and entropy encoding into two separate and individually simpler modules, the temporal instruction partitioning is applied. Following this strategy, the image processing and entropy encoding

	Serial x264	SDP x264			
Processes	1	2	4	8	16
Throughput (frames/s)	1.24	2.5	4.31	6.77	7.04
Average frame latency (ms)	642	347	179	96	89
Image Quality (Average PSNR)	39.654	39.443	39.439	39.423	39.407
Encoded Bitrate (Kb/s)	11167.78	11690.43	11746.12	11852.75	12407.42

Table 3. Performance of parallel x264 decomposed with the SDP strategy.

functions are each assigned to separate processes. The image processing thread works on frame N while the entropy encoding thread works on frame $N-1$. (As noted above, this and subsequent partitionings are original work.)

The image process finds and removes redundancy from the video stream. Having removed the redundancy, the remaining data is forwarded to the entropy encoding thread for additional compression. The entropy encoding process sends data on the output bitrate back to the image thread so that it can adjust its own computation to meet a target bitrate.

Load-balancing the TIP encoder is extremely difficult. The image processing functions are much more computationally intensive than those performing entropy encoding. In addition, a large amount of communication is required to forward the result of image processing to the entropy encoder.

Table 4 shows the performance of the serial implementation and the TIP encoder for 2 processes. As only two temporal instruction indices were identified for the H.264 encoder, that serves as a limit for the number of processes in a TIP implementation. While the throughput shows a very modest improvement, the latency of the TIP encoder is considerably worse than the serial case. This performance loss is due to the added communication of the parallelization. This strategy results in a small gain in image quality, although this is too small to be significant and likely just a lucky consequence of the test input. This slight increase in image quality also comes with a slight increase in the size of the encoded video.

	Serial x264	TIP x264
Processes	1	2
Throughput (frames/s)	1.24	1.35
Average frame latency (ms)	642	1435
Image Quality (Average PSNR)	39.654	39.659
Encoded Bitrate (Kb/s)	11167.78	11288.25

Table 4. Performance of parallel x264 decomposed with the TIP strategy.

The TIP strategy has several drawbacks when applied to x264: it is difficult to load-balance, it increased the latency, and it decreased the quality. However, it does allow the instructions to be split into two modules. Now, instead of having to handle the dependences of image processing and entropy encoding simultaneously, they can be addressed separately.

4.6 H.264 with TIP and SDP

In order to take advantage of the separation of the image processing and entropy encoding functions provided by the TIP implementation, SDP parallelism is applied to the image process. However, in this case, the frame is not split into slices, but rather rows of macroblocks. Because image processing and entropy encoding are now independent, the SDP partitioning of the image process only has to respect the data dependence of Figure 5. Thus, process P can work on macroblock row i while $P+1$ can work on $i+1$ as long as the processes synchronize so that $P+1$ does not read data from row i until it has been produced. Following this scheme, multiple processes work simultaneously on the image processing for frame N while a single process performs the entropy encoding for frame $N-1$.

As described above, each image process must send its results to the entropy process. In addition to this communication, processes responsible for image processing must communicate and synchronize to observe the dependence illustrated in Figure 5.

Load-balancing in this implementation is somewhat difficult. Even when the image processing is parallelized among as many as 15 processes, the entropy process still requires less communication. In addition, as described above for the SDP partitioning, some macroblocks require more image processing work than others, so even balancing the image processes is difficult.

Table 5 shows the performance of the serial implementation and the parallel encoder implemented with a combination of TIP and SDP. Results are shown for 2, 4, 8, 12, and 16 processes with one process always allocated to entropy encoding and the others allocated for image processing. Use of the SDP strategy in combination with TIP increases throughput and decreases latency using up to twelve processes. After that point, increasing the number of processes reduces performance due to the overhead of communication and load imbalance. However, the use of the TIP strategy to separate the image processing and entropy encoding allows the SDP pattern to be applied without resorting to the use of slices. This is reflected in the results as, unlike in the purely SDP pattern, the quality of the encoded video does not change as more processes are added.

	Serial x264	TIP+SDP x264				
Processes	1	2	4	8	12	16
Throughput (frames/s)	1.24	1.35	3.30	5.94	7.06	5.21
Average frame latency (ms)	642	1435	553	284	229	330
Image Quality (Average PSNR)	39.654	39.659	39.659	39.659	39.659	39.659
Encoded Bitrate (Kb/s)	11167.78	11288.25	11288.25	11288.2	11288.25	11288.25

Table 5. Performance of parallel x264 decomposed with a combination of the TIP and SDP strategies.

Comparing the hybrid approach using TIP and SDP represents a compromise parallelization. It does not achieve the high throughput of the pure TDP strategy, nor does it achieve the low latency of the pure SDP strategy. At the same time, the hybrid approach achieves improved throughput and latency without sacrificing the quality of the encoded image.

4.7 H.264 with TDP, TIP, and SDP

The final partitioning in the case study combines TDP, TIP, and SDP in a effort to produce a single code base that can be tuned to meet differing throughput and latency needs. In this implementation, the TDP strategy is applied to allow multiple frames to be encoded in parallel. Each frame is encoded by one or more processes. If one process is assigned to a frame, this implementation acts like the pure TDP approach. If two processes are assigned to a frame, each frame is parallelized using the TIP strategy. If three or more processes are assigned to a frame, each frame is parallelized using the combination of SDP and TIP discussed above. By applying these three strategies in one application, a variable number of frames can be encoded in parallel using a variable number of processes to encode each frame.

The communication in this implementation is the union of the required communication of the composite strategies. Processes assigned a frame must communicate reference frame data. Within a frame, the processes assigned image functions communicate results to the process assigned entropy encoding and the image processes coordinate among themselves.

The load-balancing of this implementation depends on the number of frames encoded in parallel and the number of processes assigned to each frame. If only one process encodes a single frame, the load balance is good like the pure TDP implementation. If only one frame is encoded at a time, the load balance is that of the hybrid TIP and SDP solution.

Table 6 shows the performance of the final parallelization in the case study. In this table all results are presented using sixteen processes, but the number of processes assigned to a single frame is varied. On the left side of the table, the performance is the same as the sixteen process implementation of the TIP+SDP strategy. On the left side of the table, performance is the same as the sixteen process implementation of the pure TDP strategy. The data in the middle of the table demonstrates that this approach allows a tradeoff between latency and throughput.

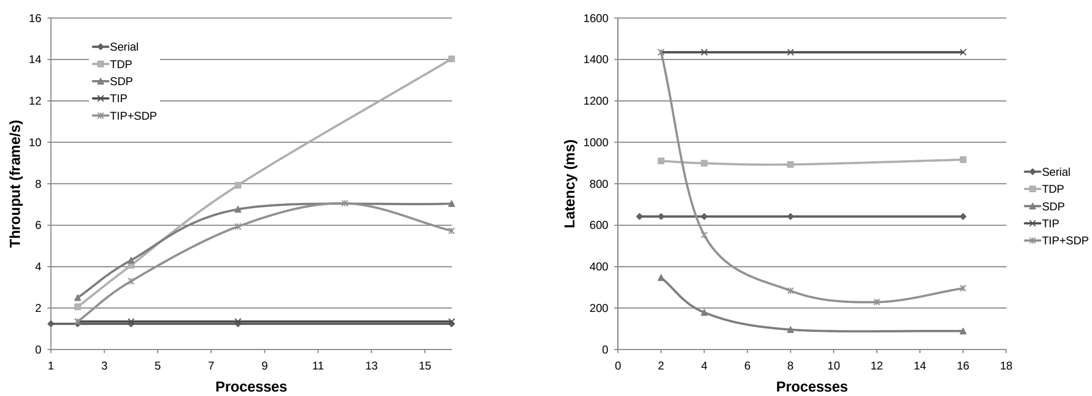
Combing the TDP, TIP, and SDP strategies creates a code base that is flexible and can be adapted to meet the needs of a particular user.

	Serial x264	TDP+TIP+SDP x264				
Parallel frames	1	1	2	4	8	16
Processes per frame	1	16	8	4	2	1
Throughput (frames/s)	1.24	5.21	7.74	11.02	12.99	14.03
Average frame latency (ms)	642	330	443	652	1151	916
Image Quality (Average PSNR)	39.654	39.659	39.652	39.652	39.646	39.654
Encoded Bitrate (Kb/s)	11167.78	11288.25	11169.48	11205.90	11224.71	11210.06

Table 6. Performance of parallel x264 decomposed with a combination of the TDP, TIP, and SDP strategies.

4.8 Summary of case study

This case study demonstrates the application of three of the four partitioning strategies to develop an H.264 encoder for HD video and it illustrates how the encoder's throughput and latency are affected by the choice of partitioning strategy. In addition, the study demonstrates how different strategies influence load balance and the ability to deal with data dependences in the parallelized application. The case study shows that the pure TDP implementation achieves the best throughput, while the pure SDP implementation achieves the best latency although with a loss of quality. The TIP implementation demonstrates that some parallelizations may not help performance but can allow complicated programs to be split into simpler modules. A hybrid approach combining TIP and SDP represents a compromise between throughput, latency, and quality. Figure 6 compares the throughput and latency of these four implementations. Finally, a combination of TDP, TIP, and SDP allows maximum flexibility in a single code base.



(a) **Throughput** (b) **Latency**

Figure 6. Performance of various parallelization strategies applied to H.264 encoder.

5 Related Work

This section discusses related work in both parallel design patterns and parallel software implementations of H.264 encoding.

5.1 Related patterns

The use of design patterns for parallel software development can add rigor and discipline to what is otherwise an ad hoc and artistic process. A number of parallel design patterns have been identified [15, 16, 19, 13, 20, 12]. These patterns range from very high-level descriptions, such as the commonly used task and data parallel patterns which may be appropriate for any application, to low-level patterns, such as a parallel hash table, which may be considered only for specific applications. Parallel pattern languages [16, 12] guide users through the application of both high and low level patterns.

Two of the most commonly invoked high-level patterns are task and data parallelism. These terms are so common that they are often used by developers who are not explicitly thinking in terms of design patterns or pattern languages. The work presented in this paper extends the task and data parallel patterns by recognizing that the tasks and data in a program have spatial and temporal components. Furthermore, partitioning in space can have a different effect on program behavior than partitioning in time. These differences are particularly relevant to applications which have both a latency and throughput requirement, such as the large class of applications that interact with the outside world.

In addition to the performance differences associated with spatial and temporal partitionings, noting the difference is useful for its descriptive power. Describing an application as exploiting spatial data parallelism provides more information than describing the same application as simply data parallel. For example, while both the TDP and SDP implementations of the video encoder are data parallel, they have fundamentally different structures, and different performance. Providing additional information enhances understanding and collaboration.

5.2 Related video encoders

Liu et al. explore a parallel implementation of a security camera which combines multiple partitioning strategies in the same application [14]. These authors first use the SIP strategy to split the search and compression functions of the camera into separate processes, each of which is further partitioned using the SDP strategy.

Rodriquez et al. describe a TDP partitioning of an H.264 encoder as well as an implementation that uses both TDP and SDP through the employment of slices [18]. Several authors describe slice-based SDP partitioning strategies [10, 3]. Jung et al. adaptively choose the slice sizes in order to address the load-balancing issue discussed above [11]. Sun et al. describe a pure SDP implementation that does not rely on slicing, but still respects the data dependences described above [21].

Park et al. apply TIP partitioning to create their parallel H.264 encoder, but rather than splitting the image and entropy functions, they split the motion estimation and analysis block of Figure 4(b) into one process and place all other functions in a second process. This implementation suffers from the same load imbalance described for the TIP implementation above. To help address this issue, SDP partitioning is applied to the motion estimation and analysis process.

6 Conclusion

This paper has presented an extension to the commonly used task and data parallel design patterns. This extension is based on the spatiotemporal nature of program execution and the different effects of parallelizing in space and time. The four strategies discussed are spatial data partitioning (SDP), temporal data partitioning (TDP), spatial instruction partitioning (SIP), and temporal instruction partitioning (TIP). A case study has demonstrated how these strategies can be applied to implement a multicore HD encoder. In addition this case study illustrates how multiple partitioning strategies can be combined to yield the benefits of each.

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