The OpenCV Library:
Computing Optical Flow

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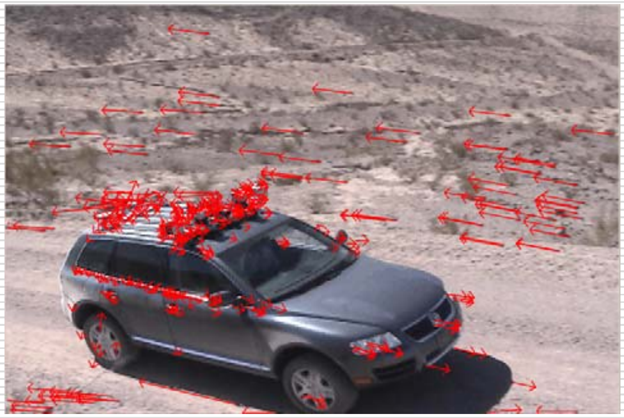
I received some requests…

- …on what to cover tonight:
- "Perhaps you could do one of the 14 projects in the course? In front of us. In one hour."
  -- Anonymous

Tonight we'll code:



A fully functional sparse optical flow algorithm!

Plan

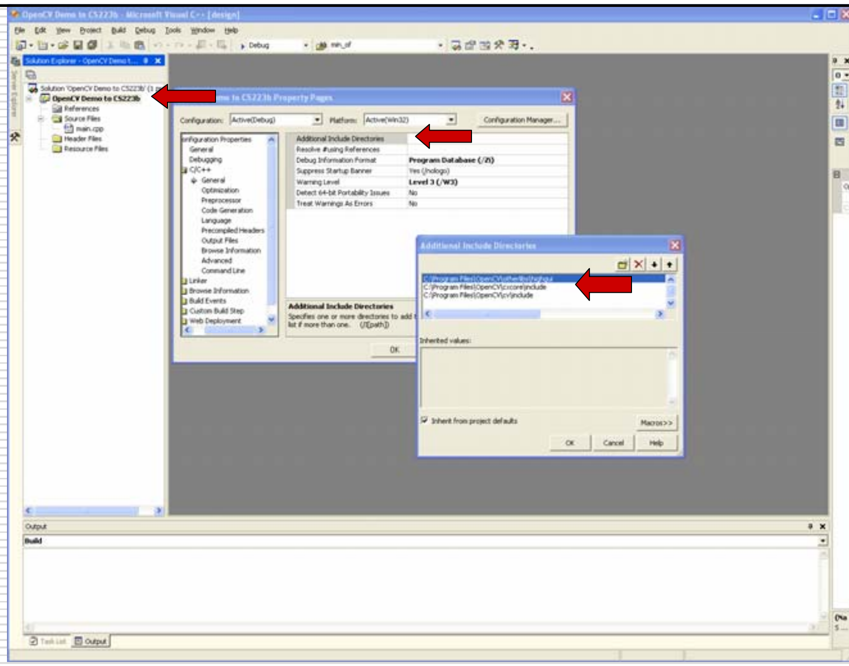
- OpenCV Basics
  - What is it?
  - How do we get started?
- Feature Finding and Optical Flow
  - A brief mathematical discussion.
- OpenCV Implementation of Optical Flow
  - Step by step.

What is OpenCV?

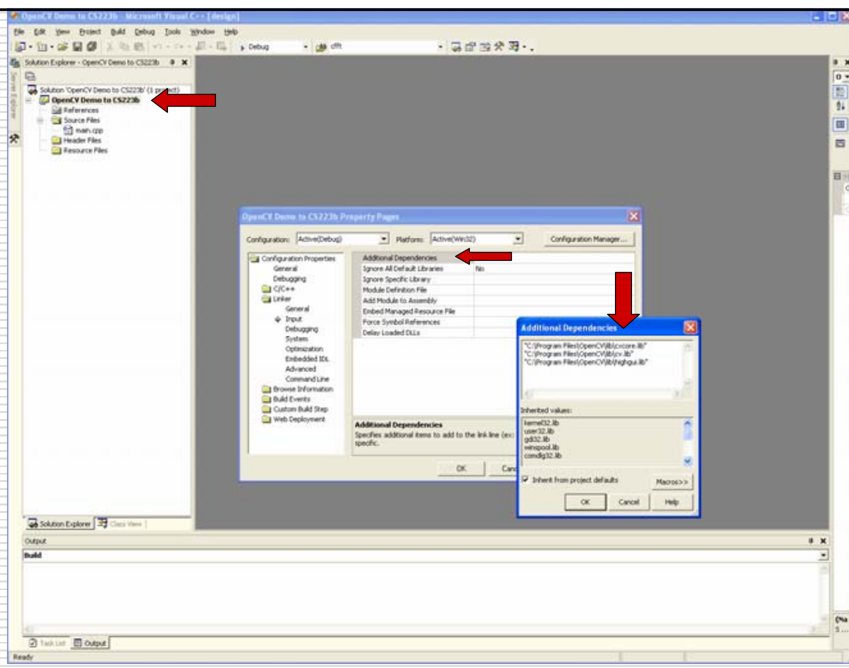
- Really four libraries in one:
  - "CV" – Computer Vision Algorithms
    - All the vision algorithms.
  - "CVAUX" – Experimental/Beta
    - Useful gems :-)
  - "CXCORE" – Linear Algebra
    - Raw matrix support, etc.
  - "HIGHGUI" – Media/Window Handling
    - Read/write AVIs, window displays, etc.
- Created/Maintained by Intel

Installing OpenCV

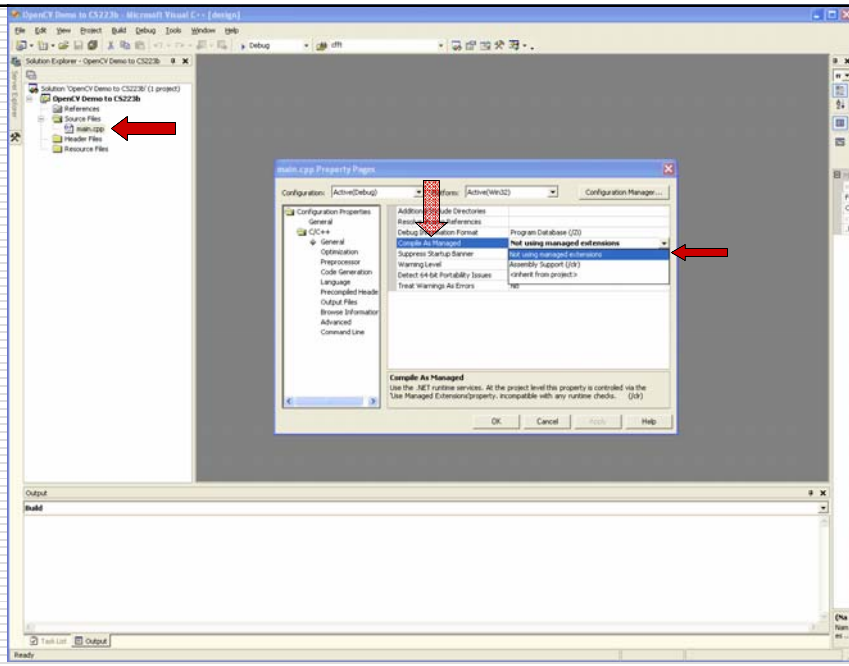
- Download from:
  - http://sourceforge.net/projects/opencvlibrary/
- Be sure to get the August 2004 release:
  - "Beta 4" for Windows XP/2000
  - "Beta 4" or "0.9.6" for Linux
- Windows version comes with an installer.
- Linux:
  - gunzip opencv-0.9.6.tar.gz; tar –xvf opencv-0.9.6.tar
  - cd opencv-0.9.6; ./configure --prefix=/usr; make
  - make install [as root]



Tell Visual Studio where the includes are.



Tell Visual Studio to link against cxcore.lib, cv.lib, and highgui.lib.



Tell Visual Studio to disable managed extensions.

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Optical Flow: Overview

- Given a set of points in an image, find those same points in another image.
- Or, given point $[u_x, u_y]^T$ in image I_1 find the point $[u_x + \delta_x, u_y + \delta_y]^T$ in image I_2 that minimizes ε:

$$\varepsilon(\delta_x, \delta_y) = \sum_{x=u_x-w_x}^{u_x+w_x} \sum_{y=u_y-w_y}^{u_y+w_y} \left(I_1(x,y) - I_2(x+\delta_x, y+\delta_y) \right)$$

- (the Σ/w's are needed due to the aperture problem)

Optical Flow: Utility

- Tracking points ("features") across multiple images is a fundamental operation in many computer vision applications:
  - To find an object from one image in another.
  - To determine how an object/camera moved.
  - To resolve depth from a single camera.
    - …or stereo.
- ~ 75% of this year's CS 223b projects.
- But what are good features to track?

Finding Features: Overview

- Intuitively, a good feature needs at least:
  - Texture (or ambiguity in tracking)
  - Corner (or aperture problem)
- But what does this mean formally?

$$\begin{bmatrix} \sum_{neighborhood} \left(\frac{\partial I}{\partial x}\right)^2 & \sum_{neighborhood} \frac{\partial^2 I}{\partial x \partial y} \\ \sum_{neighborhood} \frac{\partial^2 I}{\partial x \partial y} & \sum_{neighborhood} \left(\frac{\partial I}{\partial y}\right)^2 \end{bmatrix}$$

- A good feature has big eigenvalues, implies:
  - Texture
  - Corner
- Shi/Tomasi. Intuitive result really part of motion equation. High eigenvalues imply reliable solvability. Nice!

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So now let’s code it!

- Beauty of OpenCV:
  - All of the Above = Two Function Calls
  - Plus some support code :-)
- Let’s step through the pieces.
- These slides provide the high-level.
  - Full implementation with extensive comments:
    - http://robotics.stanford.edu/~dstavens/cs223b

Step 1: Open Input Video

CvCapture *input_video =
cvCaptureFromFile(“filename.avi”);

- Failure modes:
  - The file doesn’t exist.
  - The AVI uses a codec OpenCV can’t read.
    - Codecs like MJPEG and Cinepak are good.
    - DV, in particular, is bad.

Step 2: Get A Video Frame

```
cvQueryFrame( input_video );
```

- This is a hack so that we can look at the internals of the AVI. OpenCV doesn't allow us to do that correctly unless we get a video frame first.

Step 3: Read AVI Properties

```
CvSize frame_size;
frame_size.height =
    cvGetCaptureProperty( input_video,
    CV_CAP_PROP_FRAME_HEIGHT );
```

- Similar construction for getting the width and the number of frames.
  - See the handout.

Step 4: Create a Window

cvNamedWindow(“Optical Flow”, CV_WINDOW_AUTOSIZE);

- We will put our output here for visualization and debugging.

Step 5: Loop Through Frames

- Go to frame N:
  cvSetCaptureProperty(input_video, CV_CAP_PROP_POS_FRAMES, N);
- Get frame N:
  IplImage *frame = cvQueryFrame(input_video);
  - Important: cvQueryFrame *always* returns a pointer to the same location in memory.

Step 6: Convert/Allocate

- Convert input frame to 8-bit mono:

```
IplImage *frame1 =
    cvCreateImage( cvSize(width, height),
        IPL_DEPTH_8U, 1);
cvConvertImage( frame, frame1 );
```

- Actually need third argument to conversion: CV_CVTIMG_FLIP.

Step 7: Run Shi and Tomasi

```
CvPoint2D32f frame1_features[N];
cvGoodFeaturesToTrack(
    frame1, eig_image, temp_image,
    frame1_features, &N, .01, .01, NULL);
```

- Allocate eig,temp as in handout.
- On return frame1_features is full and N is the number of features found.

Step 8: Run Optical Flow

char optical_flow_found_feature[];
float optical_flow_feature_error[];
CvTermCriteria term =
cvTermCriteria(CV_TERMCRIT_ITER | CV_TERMCRIT_EPS, 20, .3);

cvCalcOpticalFlowPyrLK(…);

- 13 arguments total. All of the above.
  - Both frames, both feature arrays, etc.
- See full implementation in handout.

Step 9: Visualize the Output

```
CvPoint p, q;
p.x = 1; p.y = 1; q.x = 2; q.y = 2;
CvScalar line_color;
line_color = CV_RGB(255, 0, 0);
int line_thickness = 1;

cvLine(frame1, p,q, line_color, line_thickness, CV_AA, 0);
cvShowImage("Optical Flow", frame1);
```

- CV_AA means draw the line antialiased.
- 0 means there are no fractional bits.

Step 10: Make an AVI output

```
CvVideoWriter *video_writer =
    cvCreateVideoWriter( "output.avi",
    -1, frames_per_second, cvSize(w,h) );
```

- ("-1" pops up a nice GUI.)

```
cvWriteFrame(video_writer, frame);
```

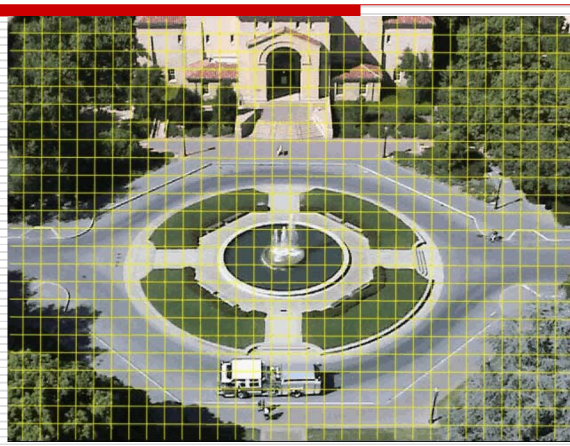
- Just like cvShowImage(window, frame);

```
cvReleaseVideoWriter(&video_writer);
```

Let's watch the result:

(The Stanford Roadrunner Robot.)

That’s the first step for…



Stavens, Lookingbill, Lieb, Thrun; CS223b 2004; ICRA 2005

A few closing thoughts…

- I’ve really described the lowest level.
- Your projects will begin with code like this and then you’ll implement something that’s not in OpenCV.
- OpenCV is good for non-vision things too.
- Feel free ask questions!
  - dstavens@robotics.stanford.edu or Gates 226
- Good luck!! 223b projects are fun :-)

```
/* --Sparse Optical Flow Demo Program--
 * Written by David Stavens (dstavens@robotics.stanford.edu)
 */
#include <stdio.h>
#include <cv.h>
#include <highgui.h>
#include <math.h>

static const double pi = 3.14159265358979323846;

inline static double square(int a)
{
    return a * a;
}

/* This is just an inline that allocates images.  I did this to reduce clutter in the
 * actual computer vision algorithmic code.  Basically it allocates the requested image
 * unless that image is already non-NULL.  It always leaves a non-NULL image as-is even
 * if that image's size, depth, and/or channels are different than the request.
 */
inline static void allocateOnDemand( IplImage **img, CvSize size, int depth, int channels ↙
     )
{
    if ( *img != NULL ) return;

    *img = cvCreateImage( size, depth, channels );
    if ( *img == NULL )
    {
        fprintf(stderr, "Error: Couldn't allocate image.  Out of memory?\n");
        exit(-1);
    }
}

int main(void)
{
    /* Create an object that decodes the input video stream. */
    CvCapture *input_video = cvCaptureFromFile(
        "C:\\Documents and Settings\\David Stavens\\Desktop\\223B-Demo\\optical_flow_input↙
    .avi"
        );
    if (input_video == NULL)
    {
        /* Either the video didn't exist OR it uses a codec OpenCV
         * doesn't support.
         */
        fprintf(stderr, "Error: Can't open video.\n");
        return -1;
    }

    /* This is a hack.  If we don't call this first then getting capture
     * properties (below) won't work right.  This is an OpenCV bug.  We
     * ignore the return value here.  But it's actually a video frame.
     */
    cvQueryFrame( input_video );

    /* Read the video's frame size out of the AVI. */
    CvSize frame_size;
    frame_size.height =
        (int) cvGetCaptureProperty( input_video, CV_CAP_PROP_FRAME_HEIGHT );
    frame_size.width =
        (int) cvGetCaptureProperty( input_video, CV_CAP_PROP_FRAME_WIDTH );

    /* Determine the number of frames in the AVI. */
    long number_of_frames;
    /* Go to the end of the AVI (ie: the fraction is "1") */
    cvSetCaptureProperty( input_video, CV_CAP_PROP_POS_AVI_RATIO, 1. );
    /* Now that we're at the end, read the AVI position in frames */
```

```
    number_of_frames = (int) cvGetCaptureProperty( input_video, CV_CAP_PROP_POS_FRAMES );
    /* Return to the beginning */
    cvSetCaptureProperty( input_video, CV_CAP_PROP_POS_FRAMES, 0. );

    /* Create three windows called "Frame N", "Frame N+1", and "Optical Flow"
     * for visualizing the output.  Have those windows automatically change their
     * size to match the output.
     */
    cvNamedWindow("Optical Flow", CV_WINDOW_AUTOSIZE);

    long current_frame = 0;
    while(true)
    {
        static IplImage *frame = NULL, *frame1 = NULL, *frame1_1C = NULL, *frame2_1C = 
    NULL, *eig_image = NULL, *temp_image = NULL, *pyramid1 = NULL, *pyramid2 = NULL;

        /* Go to the frame we want.  Important if multiple frames are queried in
         * the loop which they of course are for optical flow.  Note that the very
         * first call to this is actually not needed. (Because the correct position
         * is set outsite the for() loop.)
         */
        cvSetCaptureProperty( input_video, CV_CAP_PROP_POS_FRAMES, current_frame );

        /* Get the next frame of the video.
         * IMPORTANT!  cvQueryFrame() always returns a pointer to the _same_
         * memory location.  So successive calls:
         * frame1 = cvQueryFrame();
         * frame2 = cvQueryFrame();
         * frame3 = cvQueryFrame();
         * will result in (frame1 == frame2 && frame2 == frame3) being true.
         * The solution is to make a copy of the cvQueryFrame() output.
         */
        frame = cvQueryFrame( input_video );
        if (frame == NULL)
        {
            /* Why did we get a NULL frame?  We shouldn't be at the end. */
            fprintf(stderr, "Error: Hmm. The end came sooner than we thought.\n");
            return -1;
        }
        /* Allocate another image if not already allocated.
         * Image has ONE challenge of color (ie: monochrome) with 8-bit "color" depth.
         * This is the image format OpenCV algorithms actually operate on (mostly).
         */
        allocateOnDemand( &frame1_1C, frame_size, IPL_DEPTH_8U, 1 );
        /* Convert whatever the AVI image format is into OpenCV's preferred format.
         * AND flip the image vertically.  Flip is a shameless hack.  OpenCV reads
         * in AVIs upside-down by default.  (No comment :-))
         */
        cvConvertImage(frame, frame1_1C, CV_CVTIMG_FLIP);

        /* We'll make a full color backup of this frame so that we can draw on it.
         * (It's not the best idea to draw on the static memory space of cvQueryFrame().)
         */
        allocateOnDemand( &frame1, frame_size, IPL_DEPTH_8U, 3 );
        cvConvertImage(frame, frame1, CV_CVTIMG_FLIP);

        /* Get the second frame of video.  Sample principles as the first. */
        frame = cvQueryFrame( input_video );
        if (frame == NULL)
        {
            fprintf(stderr, "Error: Hmm. The end came sooner than we thought.\n");
            return -1;
        }
        allocateOnDemand( &frame2_1C, frame_size, IPL_DEPTH_8U, 1 );
        cvConvertImage(frame, frame2_1C, CV_CVTIMG_FLIP);

        /* Shi and Tomasi Feature Tracking! */
```

```
    /* Preparation: Allocate the necessary storage. */
    allocateOnDemand( &eig_image, frame_size, IPL_DEPTH_32F, 1 );
    allocateOnDemand( &temp_image, frame_size, IPL_DEPTH_32F, 1 );

    /* Preparation: This array will contain the features found in frame 1. */
    CvPoint2D32f frame1_features[400];

    /* Preparation: BEFORE the function call this variable is the array size
     * (or the maximum number of features to find).  AFTER the function call
     * this variable is the number of features actually found.
     */
    int number_of_features;

    /* I'm hardcoding this at 400.  But you should make this a #define so that you can
     * change the number of features you use for an accuracy/speed tradeoff analysis.
     */
    number_of_features = 400;

    /* Actually run the Shi and Tomasi algorithm!!
     * "frame1_1C" is the input image.
     * "eig_image" and "temp_image" are just workspace for the algorithm.
     * The first ".01" specifies the minimum quality of the features (based on the eigenvalues).
     * The second ".01" specifies the minimum Euclidean distance between features.
     * "NULL" means use the entire input image.  You could point to a part of the image.
     * WHEN THE ALGORITHM RETURNS:
     * "frame1_features" will contain the feature points.
     * "number_of_features" will be set to a value <= 400 indicating the number of feature points found.
     */
    cvGoodFeaturesToTrack(frame1_1C, eig_image, temp_image, frame1_features, & number_of_features, .01, .01, NULL);

    /* Pyramidal Lucas Kanade Optical Flow! */

    /* This array will contain the locations of the points from frame 1 in frame 2. */
    CvPoint2D32f frame2_features[400];

    /* The i-th element of this array will be non-zero if and only if the i-th feature of
     * frame 1 was found in frame 2.
     */
    char optical_flow_found_feature[400];

    /* The i-th element of this array is the error in the optical flow for the i-th feature
     * of frame1 as found in frame 2.  If the i-th feature was not found (see the array above)
     * I think the i-th entry in this array is undefined.
     */
    float optical_flow_feature_error[400];

    /* This is the window size to use to avoid the aperture problem (see slide "Optical Flow: Overview"). */
    CvSize optical_flow_window = cvSize(3,3);

    /* This termination criteria tells the algorithm to stop when it has either done 20 iterations or when
     * epsilon is better than .3.  You can play with these parameters for speed vs. accuracy but these values
     * work pretty well in many situations.
     */
    CvTermCriteria optical_flow_termination_criteria
        = cvTermCriteria( CV_TERMCRIT_ITER | CV_TERMCRIT_EPS, 20, .3 );
```

```
        /* This is some workspace for the algorithm.
         * (The algorithm actually carves the image into pyramids of different resolutions↙
    .)
         */
        allocateOnDemand( &pyramid1, frame_size, IPL_DEPTH_8U, 1 );
        allocateOnDemand( &pyramid2, frame_size, IPL_DEPTH_8U, 1 );

        /* Actually run Pyramidal Lucas Kanade Optical Flow!!
         * "frame1_1C" is the first frame with the known features.
         * "frame2_1C" is the second frame where we want to find the first frame's        ↙
    features.
         * "pyramid1" and "pyramid2" are workspace for the algorithm.
         * "frame1_features" are the features from the first frame.
         * "frame2_features" is the (outputted) locations of those features in the second ↙
    frame.
         * "number_of_features" is the number of features in the frame1_features array.
         * "optical_flow_window" is the size of the window to use to avoid the aperture   ↙
    problem.
         * "5" is the maximum number of pyramids to use.  0 would be just one level.
         * "optical_flow_found_feature" is as described above (non-zero iff feature found ↙
    by the flow).
         * "optical_flow_feature_error" is as described above (error in the flow for this ↙
    feature).
         * "optical_flow_termination_criteria" is as described above (how long the        ↙
    algorithm should look).
         * "0" means disable enhancements.  (For example, the second aray isn't pre-       ↙
    initialized with guesses.)
         */
        cvCalcOpticalFlowPyrLK(frame1_1C, frame2_1C, pyramid1, pyramid2, frame1_features, ↙
    frame2_features, number_of_features, optical_flow_window, 5,                         ↙
    optical_flow_found_feature, optical_flow_feature_error,                               ↙
    optical_flow_termination_criteria, 0 );

        /* For fun (and debugging :)), let's draw the flow field. */
        for(int i = 0; i < number_of_features; i++)
        {
            /* If Pyramidal Lucas Kanade didn't really find the feature, skip it. */
            if ( optical_flow_found_feature[i] == 0 )   continue;

            int line_thickness;             line_thickness = 1;
            /* CV_RGB(red, green, blue) is the red, green, and blue components
             * of the color you want, each out of 255.
             */
            CvScalar line_color;            line_color = CV_RGB(255,0,0);

            /* Let's make the flow field look nice with arrows. */

            /* The arrows will be a bit too short for a nice visualization because of the ↙
    high framerate
             * (ie: there's not much motion between the frames).  So let's lengthen them  ↙
    by a factor of 3.
             */
            CvPoint p,q;
            p.x = (int) frame1_features[i].x;
            p.y = (int) frame1_features[i].y;
            q.x = (int) frame2_features[i].x;
            q.y = (int) frame2_features[i].y;

            double angle;       angle = atan2( (double) p.y - q.y, (double) p.x - q.x );
            double hypotenuse;  hypotenuse = sqrt( square(p.y - q.y) + square(p.x - q.x) )↙
    ;

            /* Here we lengthen the arrow by a factor of three. */
            q.x = (int) (p.x - 3 * hypotenuse * cos(angle));
            q.y = (int) (p.y - 3 * hypotenuse * sin(angle));

            /* Now we draw the main line of the arrow. */
```

```
            /* "frame1" is the frame to draw on.
             * "p" is the point where the line begins.
             * "q" is the point where the line stops.
             * "CV_AA" means antialiased drawing.
             * "0" means no fractional bits in the center cooridinate or radius.
             */
            cvLine( frame1, p, q, line_color, line_thickness, CV_AA, 0 );
            /* Now draw the tips of the arrow.  I do some scaling so that the
             * tips look proportional to the main line of the arrow.
             */
            p.x = (int) (q.x + 9 * cos(angle + pi / 4));
            p.y = (int) (q.y + 9 * sin(angle + pi / 4));
            cvLine( frame1, p, q, line_color, line_thickness, CV_AA, 0 );
            p.x = (int) (q.x + 9 * cos(angle - pi / 4));
            p.y = (int) (q.y + 9 * sin(angle - pi / 4));
            cvLine( frame1, p, q, line_color, line_thickness, CV_AA, 0 );
        }
        /* Now display the image we drew on.  Recall that "Optical Flow" is the name of
         * the window we created above.
         */
        cvShowImage("Optical Flow", frame1);
        /* And wait for the user to press a key (so the user has time to look at the 
    image).
         * If the argument is 0 then it waits forever otherwise it waits that number of 
    milliseconds.
         * The return value is the key the user pressed.
         */
        int key_pressed;
        key_pressed = cvWaitKey(0);

        /* If the users pushes "b" or "B" go back one frame.
         * Otherwise go forward one frame.
         */
        if (key_pressed == 'b' || key_pressed == 'B')   current_frame--;
        else                                            current_frame++;
        /* Don't run past the front/end of the AVI. */
        if (current_frame < 0)                      current_frame = 0;
        if (current_frame >= number_of_frames - 1)  current_frame = number_of_frames - 2;
    }
}
```