Invariant subspace methods for CAREs

X solves CARE $A^*X + XA + Q = XGX$ iff

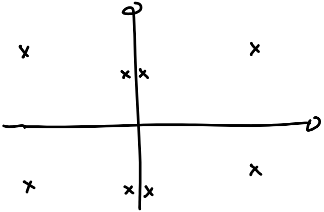
$$\begin{bmatrix} A & -G \\ -Q & -A^T \end{bmatrix} \begin{bmatrix} I \\ X \end{bmatrix} = \begin{bmatrix} I \\ X \end{bmatrix} \mathcal{R}, \quad \mathcal{R} = A - GX.$$

One can find X through an invariant subspace of the Hamiltonian.

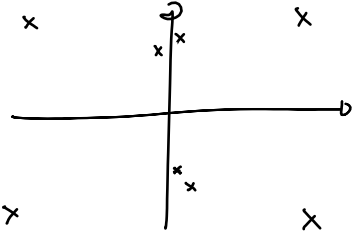
```
>> [A,G,Q] = carex(4) %if test suite is installed
>> n = length(A);
>> H = [A -G; -Q -A'];
>> [U, T] = schur(H);
>> [U, T] =ordschur(U, T, 'lhp');
>> X = U(n+1:2*n, 1:n) / U(1:n, 1:n);
```

People are not satisfied with this method though — it is not structured backward stable.

Eigenvalues close to the imaginary axis can be 'mixed up' — try `carex(14)` for instance.



Un metodo di Schur potrebbe produrre



Vorremmo un metodo che ci assicuri che
gli autoval. hanno la struttura richiesta.

Se

$$\mathcal{H} = \begin{bmatrix} U_1 & U_3 \\ U_2 & U_4 \end{bmatrix} \begin{bmatrix} T_{11} & T_{12} \\ 0 & T_{22} \end{bmatrix} \begin{bmatrix} U_1 & U_3 \\ U_2 & U_4 \end{bmatrix}^T,$$

allora $\operatorname{span}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}$ è un sottospazio invariante: (associato agli autovalori di T_{11}).

$$\mathcal{H}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \underbrace{\begin{bmatrix} U_1 & U_3 \\ U_2 & U_4 \end{bmatrix} \underbrace{\begin{bmatrix} T_{11} & T_{12} \\ 0 & T_{22} \end{bmatrix} \underbrace{\begin{bmatrix} U_1 & U_3 \\ U_2 & U_4 \end{bmatrix}^T \begin{bmatrix} U_1 \\ U_2 \end{bmatrix}}_{= \begin{bmatrix} I \\ 0 \end{bmatrix}}}_{= \begin{bmatrix} T_{11} \\ 0 \end{bmatrix}}}_{= \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} T_{11}}$$

$$X = U_2 U_1^{-1}$$

Symplectic transformations

Ideal setting: make transformations at each step that are orthogonal and symplectic, i.e., orthogonal w.r.t the scalar product $J = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$: they satisfy $S^T J S = J$.

For instance:

- If $Q \in \mathbb{R}^{n \times n}$ is any orthogonal matrix, then blkdiag(Q, Q) is orthogonal and symplectic.
- A Givens matrix that acts on entries k and $n + k$ (i.e., `G = eye(2*n); G([k,n+k], [k,n+k]) = [c s; -s c];`) is orthogonal and symplectic.

Def: $S \in \mathbb{C}^{2n \times 2n}$ si dice simplettica se

$\langle v, w \rangle_J = \langle Sv, Sw \rangle_J$ per ogni $v, w \in \mathbb{C}^{2n}$

cioè $v^* J w = v^* S^* J S w \quad \forall v, w \iff J = S^* J S$

$S^* = J S^{-1} J$

Lemma: se H Hamiltoniana, S simplettica, $S^{-1} H S$ è Hamiltoniana: $\boxed{JH = -H^* J}$

$$(S^{-1} H S)^* = S^* H^* S^{-*} = J S^{-1} J \, J H J \, J S J =$$

$$= J (S^{-1} H S) J$$

$$J (S^{-1} H S) = (S^{-1} H S)^* J^{-1} = -(S^{-1} H S) J$$

Laub trick: let $U = \begin{bmatrix} U_1 & U_3 \\ U_2 & U_4 \end{bmatrix}$ the unitary matrix produced by (ord) `schur(H)`. Then, $\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}$ is an orthogonal matrix that spans the stable subspace. We know that $-J \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} U_2 \\ -U_1 \end{bmatrix}$ is orthogonal to it (and spans the left unstable invariant subspace).

It turns out that $V = \begin{bmatrix} U_1 & U_2 \\ U_2 & -U_1 \end{bmatrix}$ is orthogonal and symplectic, and $V^T \mathcal{H} V = \begin{bmatrix} R & S \\ 0 & -R^* \end{bmatrix}$, with R upper triangular and S symmetric (Hamiltonian Schur form).

$$H \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} R$$

perché $\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}$ spanno un sott. invariante $=0$

$$H \begin{bmatrix} U_1 & * \\ U_2 & * \end{bmatrix} = \begin{bmatrix} U_1 & * \\ U_2 & * \end{bmatrix} \begin{bmatrix} R & * \\ 0 & * \end{bmatrix}$$

Prendo $\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}$ prodotto dal metodo di Schur,

e ci attacco $-J\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} -U_2 \\ U_1 \end{bmatrix}$,

ottenendo

$S = \begin{bmatrix} U_1 & -U_2 \\ U_2 & U_1 \end{bmatrix}$. Risultato: S è ortogonale e simplettica:

1) $S^*S = \begin{bmatrix} U_1^* & U_2^* \\ -U_2^* & U_1^* \end{bmatrix}\begin{bmatrix} U_1 & -U_2 \\ U_2 & U_1 \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$ (perché $\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}$ ha col. orto.)

$U_1^*U_2 - U_2^*U_1$,

che è la relazione $\begin{bmatrix} U_1^* & U_2^* \end{bmatrix} J \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = 0$

2) $J \overset{?}{=} S^* J S$

$$S^* J S = \begin{bmatrix} U_1^* & U_2^* \\ -U_2^* & U_1^* \end{bmatrix} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} U_1 & -U_2 \\ U_2 & U_1 \end{bmatrix} =$$

$$= \begin{bmatrix} U_1^* & U_2^* \\ -U_2^* & U_1^* \end{bmatrix} \begin{bmatrix} U_2 & U_1 \\ -U_1 & U_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

An orthogonal symplectic algorithm

This produces the same subspace as the previous method, so it is not really a 'structured' method. Can one do a 'symplectic QR' and compute the Hamiltonian Schur form using a sequence of orthosymplectic transformations?

Open problem for a while; it turns out that that Schur form does not exist for all Hamiltonian matrices (there are counterexamples with eigenvalues on the unit circle). $\implies$ algorithms must be unstable 'nearby'.

(This problem was known as Van Loan's curse.)

Chu–Liu–Mehrmann algorithm

Closest thing to a solution: Chu–Liu–Mehrmann algorithm. Based on a different decomposition: $\mathcal{H} = URV^T$, with U, V orthosymplectic and

$$R = \begin{bmatrix} R_{11} & R_{12} \\ 0 & R_{22} \end{bmatrix}$$

with R_{11}, R_{22}^* upper triangular.
Can be computed 'almost' directly in $O(n^3)$ (it's an LU-like decomposition).

Note that

$$\mathcal{H} = V \begin{bmatrix} -R_{22}^T & R_{12}^T \\ 0 & -R_{11}^T \end{bmatrix} U^T.$$

Hence

$$\mathcal{H}^2 = V \begin{bmatrix} -R_{11} R_{22}^T & * \\ 0 & -R_{22} R_{11}^T \end{bmatrix} V^T$$

can be used to compute eigenvalues and eigenvectors (for instance: the columns of V cause early breakdown in Arnoldi).